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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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AGARD CONFERENCE PROCEEDINGS 511

Insensitive Munitions

(Les Munitions à Risque Atténué)

Papers presented at the Propulsion and Energetics Panel 78th A Specialists' Meeting held in Bonn, Germany, 21st—23rd October 1991.

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North Atlantic Treaty Organization

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AGARD CP 353, January 1984

Hazard Studies for Solid Propellant Rocket Motors
AGARD CP 367, September 1984

Engine Cyclic Durability by Analysis and Testing
AGARD CP 368, September 1984

Gears and Power Transmission Systems for Helicopters and Turboprops
AGARD CP 369, January 1985

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AGARD CP 391, January 1986

Interior Ballistics of Guns
AGARD CP 392, January 1986

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Transonic and Supersonic Phenomena in Turbomachines
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ADVISORY REPORTS (AR)

Through Flow Calculations in Axial Turbomachines *(Results of Working Group 12)*
AGARD AR 175, October 1981

Alternative Jet Engine Fuels *(Results of Working Group 13)*
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Producibility and Cost Studies of Aviation Kerosines *(Results of Working Group 16)*
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AGARD LS 169, May 1990

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AGARD LS 180, June 1991

Steady and Transient Performance Prediction of Gas Turbine Engines
AGARD LS 183, May 1992

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Manual for Aeroelasticity in Turbomachines
AGARD AG 298/1, March 1987
AGARD AG 298/2, June 1988

Measurement Uncertainty within the Uniform Engine Test Programme
AGARD AG 307, May 1989

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AGARD AG 316, September 1990

REPORTS (R)

Application of Modified Loss and Deviation Correlations to Transonic Axial Compressors
AGARD R 745, November 1987

Rotorcraft Drivetrain Life Safety and Reliability
AGARD R 775, June 1990

Theme

"Insensitive Munitions" is an important area to NATO in light of the recent initiative by CNAD to develop a NATO Insensitive Munitions Information Centre (NIMIC) in Brussels in 1991. Insensitive munition requirements, evolving in NATO and many individual nations, are aimed at reducing the potential for and effects of *unintended activation of munitions* caused by their exposure to environmental forces. Such forces can occur either normally in situations such as transport and storage, in accidents such as fire, or combat circumstances through impact from bullets and fragments. The scope of the meeting focused on hazard technologies associated with rocket propulsion but also included other munition components that would be included in an overall safety assessment of a missile system. The scope was:

- requirements in NATO Nations
- approaches for hazard assessment
- studies on hazard threat areas
- studies on hazard technology areas
- development of new energetic material and
- development of devices to reduce destructive response to stimuli.

Thème

"Les Munitions à Risque Atténué" est un domaine désormais important pour l'OTAN, suite à l'initiative prise par le CNAD visant à la création d'un centre de renseignements OTAN sur les munitions à risque atténué (NIMIC) à Bruxelles pour l'année 1991.

Les spécifications des munitions à risque atténué, qui sont en cours d'élaboration au sein de l'OTAN, ainsi que dans de nombreux pays, ont pour objet la réduction du potentiel et des effets de l'amorçage involontaire des munitions suite à leur exposition aux forces externes. De telles forces se manifestent soit en temps normal, lors des opérations de transport et de stockage par exemple, soit en cas d'accident tel qu'une incendie, soit en situation de combat lors de l'impact de balles et d'éclats.

La réunion a mis l'accent sur les technologies du risque associées à la propulsion par fusée, tout en incluant les autres éléments constitutifs du système qui étaient à prendre en compte lors de l'évaluation des risques présentés par un système de missiles.

La réunion a examiné les sujets suivants:

- les besoins exprimés par les pays membres de l'OTAN
- les approches possibles de l'évaluation du risque
- les études sur les domaines à grand risque
- les études sur les technologies du risque
- le développement de nouvelles matières énergétiques
- le développement d'appareils destinés à réduire la réponse destructive aux stimuli.

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Contents

TECHNICAL EVALUATION REPORT

by

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1.0 SUMMARY

This meeting provided a forum for technical interchange between insensitive munitions policy makers from the North American Treaty Organization (NATO) countries and the research and development technologists of the Advisory Group for Aerospace Research and Development (AGARD). The objectives of the meeting, which are described below, were achieved. It was also concluded that, although not all countries have insensitive munitions policies, they all support insensitive munitions, at least in principle, and that a great deal of additional work needs to be conducted to accurately predict from small-scale tests the response of full-scale munition to hazard stimuli.

2.0 INTRODUCTION

The objectives of this specialist meeting were as follows: (a) review the insensitive munitions policies of the NATO member nations, (b) discuss the status and results of research and development programs in the member nations that address insensitive munitions, (c) identify new ideas for research, and (d) stimulate interchange and communication between research and development scientists within member countries who are addressing insensitive munitions. This meeting was very timely and addressed an important NATO issue, in light of the recent initiative by the Conference of National Armaments Directors (CNAD) to develop a NATO Insensitive Munitions Information Center (NIMIC) in Brussels in 1991.

NATO policy and technical specialists in the following areas were represented: (a) insensitive munitions requirements and policy, (b) high explosives, (c) gun propulsion, (d) rocket propulsion, and (e) energetic materials and physical phenomena research. The meeting involved twenty four papers, plus a keynote address, and was organized in the following categories:

- Insensitive munitions policy
- Explosives and gun propulsion
- Rocket propulsion
- Physical phenomena associated with insensitive munitions.

3.0 BACKGROUND

More than 6000 people have been killed during this century as a result of hazards created by munitions responding to unplanned stimuli such as heat or shock. The largest of such events was the collision of a Belgium boat with a French cargo ship loaded with ammunition in the harbor of Halifax, Nova Scotia, Canada, on 12 December 1917, which resulted in approximately 5000 deaths (Reference 1). In response to these accidents, several NATO countries initiated the definition of requirements and policies

addressing insensitive munitions. The NATO Group AC/310, one of six cadre groups under CNAD, was formed in 1979 to address the need for standardization of weapons systems, with emphasis on energetic materials. Specifically, NATO Group AC/310 was tasked to establish a common international terminology and develop design principles, criteria, procedures, and tests to cover all aspects of the process by which weapons systems are assessed to be safe and suitable for service. Propulsion and ordnance systems, therefore, are only one of the NATO Group AC/310's responsibilities (Reference 2).

NATO Group AC/310 envisioned the need for a mechanism to disseminate information within NATO member countries and hosted a workshop, entitled "Insensitive Munitions Information Exchange," in 1986 (Reference 3). This workshop confirmed the need and justification for an insensitive munitions information exchange system within NATO. In 1988, NATO Group AC/310 established a Pilot NATO Insensitive Munitions Information Center (PNIMIC) to validate and justify the need and operational concept of this information exchange system. The PNIMIC was successful, and the formal NATO Insensitive Munitions Information Center (NIMIC) was established in May 1991 in Brussels, Belgium (1).*

At about the same time that NATO Group AC/310 was addressing the insensitive munitions information exchange mechanism, AGARD became interested in the technology associated with alleviating the hazards of energetic materials and its application to propulsion systems and warheads. In 1984, AGARD hosted a Conference entitled "Hazards Studies for Solid Propellant Rocket Motors" (Reference 4). During this meeting, technical interactions between AGARD and NATO standardization activities provided the basis for improved hazard methodologies to be used in the design of future solid propellant rocket motors. In addition, a basis was provided for new research and development topics to be addressed by the different NATO countries interested in the development, production, and operation of high-energy, solid propellant rocket motors.

The second conference, in 1986, focused on smokeless propellants (Reference 5). It highlighted the severe problems encountered by propellant formulators in trying to develop insensitive smokeless propellants, while maintaining performance. The need for an "AGARDograph" (Reference 1) to document the status of hazard studies within NATO member nations was identified at the conference.

4.0 EVALUATION

Rear Admiral Meinig's (U. S. Naval Sea Systems Command) keynote address reemphasized the need for insensitive munition requirements and international research collaboration which would result in better solutions reached in a shorter time. The U.S. Joint-Service Insensitive Requirements, and desired munition response, were reiterated. Munitions should satisfactorily pass the following hazard tests: fast cookoff, slow cookoff, fragment attack, bullet impact, sympathetic detonation, spall attack, and shape charge attack. It was emphasized that the requirement for ammunition to pass these hazard tests must compete with other system requirements, such as cost and performance; all requirements must interact to optimize the overall system and meet the users' needs. The keynote address focused the attention of conference attendees to the need for insensitive munitions and the need to share information in order to more rapidly solve problems.

The four major sessions of the conference are discussed and evaluated in the following sections.

* Number in parentheses refers to paper number in the meeting.

4.1 Insensitive Munitions Policy

This session contained four papers which addressed insensitive munitions policies and information exchange procedures practiced by various member nations. The paper presented by Defourneaux (1) gave an excellent overview of the history of PNIMIC and NIMIC, as well as informing the attendees on how to add information to NIMIC's database and have NIMIC conduct literature searches on spec'fic insensitive munition subjects.

Shepard (2) stated that the U.K. has no formal statute on insensitive munitions; however, it has a Joint Insensitive Munitions Working Group that tries to meet performance and readiness requirements with the least sensitive munition. Even without a formal requirement, the U.K. has a policy to analyze and study vulnerability and its trade-off against weapon system cost and effectiveness.

Saliou (3) presented France's requirements, which are quite similar to U.S. requirements, except for spall attack, which France does not have. France's insensitive munition reponse requirements are defined as follows: (a) no reaction except burning for fast cookoff, drop, bullet impact, and light fragment attack; (b) no detonation response for heavy fragment attack and sympathetic detonation; and (c) no specified response for slow cookoff.

The final paper, of this session, by Lamy (4) addressed trade-off studies for projectile explosives and propellants. It was found that combustible cases, in place of metallic cases, reduce the sensitivity of shells when exposed to the required hazard tests. Data on high explosives (pressed PBXs) with triaminotrinitrobenzene (TATB) showed reduced sensitivity, but also markedly reduced performance. Some very interesting data presented indicated that, if the design of a system allows the projectile penetrating energetic material to stay ahead of the shock wave, then a detonation will not result from bullet impact or fragment attack. Lamy also reiterated that a balance between performance, vulnerability, and cost has to be achieved.

4.2 Explosives and Gun Propulsion

The second session addressed explosives and gun propellants and contained six papers. The paper by Jenus (5), presented by Day, described the U.S. Air Force program for techniques to reduce the quantity/distance requirements for bombs in mass storage; this would result in significant increases in combat effectiveness at airfields. By using buffer materials between the stacks of bombs, the packing density of the bombs could be doubled. These buffer materials could even be other types of ammunition, such as boxes of 25-mm cartridges.

The paper by May (6) described a novel electromagnetic (EM) gun system that does not require any energetic materials to propel the projectile. However, EM gun power trains (high-density electrical energy storage and power supplies) may in themselves induce separate hazards unforeseen at this time.

Held (7) provided a review of insensitive munition testing techniques and definitions used throughout NATO member countries. Couturier (8) presented experimental results on an especially designed warhead loaded with cast PBX that passed all of the insensitive munition tests. This particular warhead included an absorbing material between the explosive and warhead case and employed a venting device; this concept proved to be less sensitive to hazard stimuli than a similar design without the absorbing material. The design principles used were as follows: (a) use explosives with high initiation pressures and good thermal and mechanical properties; (b) employ shock absorbing materials at the interface of the explosive and warhead case; and (c) employ venting devices.

The last two papers (9 and 10) of this session dealt with the sensitivity of cyclotrimethylenetrinitramine (RDX) and cyclotetramethylenetetranitramine (HMX) and the effects of crystal shape and defects. Vander Steen (9) presented data showing the influence of RDX crystal shape and defects on the sensitivity of a RDX/polyurethane formulation, while Hooton (10) (presented by Lessard) presented data showing that identical formulations using HMX in place of RDX were less sensitive, yet provided higher performance.

4.3 Rocket Propulsion

The third session addressed rocket propulsion and propellants and contained five papers. Merrill (11) presented an excellent summary of ongoing work in electrostatic discharge abatement. The paper described a subscale test technique that allows samples to be tested under pressure and at varying temperatures. Data on breakdown voltage vs. pressure and sample bulk temperature of hydroxyl-terminated polybutadiene (HTPB) propellants were presented.

The next two papers by Lessard (12) and Menke (13) addressed formulation studies for minimum-smoke and low-sensitivity rocket propellants. Lessard (12) presented data on a glycidyl azide polymer and ammonium nitrate oxidizer formulation that, to date, has not met the target performance, burning rate, or mechanical properties of the program. The program is continuing to address these shortfalls by looking at other oxidizers and additives. Menke (13) described a nitroguanidine-oxidized formulation that has reduced sensitivity if it is contained in a motor tube that ruptures easily during hazard testing. Nitroguanidine was used to eliminate HCl from the exhaust products. However, during questioning, Menke stated that aluminum would have to be added to the formulation to achieve adequate performance. The Evaluator notes that this would result in primary smoke (Al_2O_3), and therefore eliminating the concern for HCl (secondary smoke).

The final two papers of this session by Mason (14) and Hartman (15) addressed various aspects of rocket motor hardware and propellant hazards testing. Mason (14) gave an overview of a very large British database of propellant formulations and rocket motor case designs that have been subjected to hazard testing. Of interest was the apparent lack of correlation between pass/fail of Class 1.1 and 1.3 propellant formulations when they are subjected to a 0.5-inch-diameter bullet impact. Additional data presented showed that all elastomer-modified, cast double-based (EMCDB) propellant formulations react in approximately 60 seconds, independent of case design, when subjected to a fast cookoff test. Hartman's paper (15) summarized a great deal of data on the testing of minimum-smoke propellants with ammonium perchlorate (AP) or potassium perchlorate (KP) as oxidizers. The KP formulation has significant potential for high-density propellant applications. A laser safe/arm igniter concept was described that may alleviate some of the sensitivity caused by the igniter components in rocket motors. Data comparing several types of rocket motor case materials and their response to hazard stimuli were also provided.

4.4 Physical Phenomena Associated With Insensitive Munitions

The fourth and final session of the conference covered the physical phenomena associated with energetic materials responding to hazard stimuli, both in terms of testing and modelling. This session contained nine papers. The opening paper of this session, presented by Boggs (16), described a collaborative effort of The Technical Cooperation Program (TTCP), Panel W, Action Group 11 (WAG-11). This effort consists of developing hazard assessment protocols and their uses for each of the hazard threats. These protocols, available through NIMIC, will be further discussed in the recommendations section of this report.

Brunet (17) compared some fragment and bullet impact experimental results with modelling results obtained with the LS-DYNA-2D computer code. The two sets of data correlated very well and indicated that tension waves, caused by a projectile or fragment penetrating an undamaged propellant mass, sensitize the propellant. If this occurs at the right projectile velocity, it will cause an XDT reaction.

The next paper (18), presented by Shepard, described an analytical and experimental program that evaluated projectiles that transmit a one-dimensional shock into a cased explosive. Some of the variables tested were case thickness, case material, projectile velocity, and projectile shape.

Wanninger (19) covered the results obtained in three different study areas and summarized his conclusions as follows: (a) an explosive material with good mechanical properties is required in order to pass the fuel fire cookoff test; (b) the ammunition caliber and the critical diameter of the explosive have a significant influence in bullet impact safety; and (c) the more brittle the explosive, the more susceptible it will be to shape charge attack.

Lindfors (20) briefed the audience only on the portion of a three-part paper that regarded shock sensitivity of propellants in the wedge test. This study led to insights into the influence of certain components of energetic composite materials in the shock-to-detonation reaction. The other two parts of the paper dealt with delayed detonations of propellant impacted by a projectile, and munition response predictions using the FRAG-MAP code, which is a development based on the hazard assessment protocols discussed by Boggs.

The degree of confinement of a plastic-bonded explosive significantly influences the degree of reaction to a cookoff hazard stimulus. Farinaccio's (21) results demonstrated this, as well as the influence that the heating rate has on the temperature at which the reaction will occur. Fournier (22) used one-dimensional and three-dimensional computer analysis to model three areas of concern associated with a fire in ship compartments: (a) heat transfer between compartments and containers; (b) hot gas/exhaust jet impacting on a flat plate surface; and (c) thermal response of warhead and rocket units in the compartments.

Pessica (23) showed that, by adding external user subroutines to the two-dimensional finite difference coupled Lagrangian-Eulerian PISCES code, it is possible to perform a very wide range of useful shock-to-detonation transition predictions under most circumstances.

The final paper of the conference, by Nouguez (24), demonstrated that current cast PBXs, with confinement modifications, can meet all the insensitive munitions tests, except sympathetic detonation. Two new cast PBXs have been formulated using nitrotriazolone (NTO) as the primary energetic ingredient. DYNA-2D models and experimental tests have shown that these cast PBXs can successfully pass the sympathetic detonation test and can perform fairly satisfactorily in slow cookoff, fast cookoff, bullet impact, and fragment attack tests.

5.0 CONCLUSIONS

While large-scale go/no go tests are important to demonstrate insensitive munitions compliance, they lack in other areas: (a) they are inadequate by themselves because they cannot be well instrumented and, therefore, valuable lessons are hard to learn from their final outcome; (b) they are too costly for the amount of infomation they provide; moreover, because they are conducted at the end of a weapon's development program, any problems identified during these tests are also very costly to fix; and, finally, (c) they are poor statistically (most hazard requirements demand 1:10^6 probabilities).

As a result, small-scale tests need to be validated and accepted so that their results can be included in the statistical probability of failure prediction of the all-up system.

6.0 RECOMMENDATIONS

Recommendations based on the outcome of this meeting are as follows:

1. The use of hazard protocols should be supported and encouraged. NATO member countries should use and evaluate the protocols, exchange the results, and, through a coordinating AGARD/PEP working group, compare and document the outcome.

2. All AGARD/PEP members should be encouraged to support and publicize NIMIC and its capabilities.

3. Fundamental research on the mechanisms that trigger violent responses during cookoff should be supported and encouraged. Of particular importance are the following: (a) the thermochemical and thermomechanical mechanisms that trigger the violent response of energetic materials under confinement during a fast cookoff; (b) the thermochemical and thermomechanical mechanisms that trigger the violent response of energetic materials during slow cookoff; and (c) the elevated temperature chemical mechanisms occurring in bulk propellant during slow cookoff.

7.0 REFERENCES

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3. *Workshop on Insensitive Munitions Information Exchange*, 13-15 October 1986, published March 1987. NATO AC/310 Conference Proceedings No. 001.

4. *Hazards Studies for Solid Rocket Motors*. AGARD Specialists Meeting, 28-30 May 1984, published September 1984. AGARD Conference Proceedings No. 367

5. *Smokeless Propellants*. AGARD Specialists Meeting, 12-13 September 1985, published January 1986. AGARD Conference Proceedings No. 391

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Nato Insensitive Munitions Information Center

NIMIC

Centre Otan d'information sur les munitions à risque atténué

SUMMARY

Having proven its value during a three-year Pilot phase, the NATO Insensitive Munitions Information Center began operations in NATO Headquarters, Brussels in May 1991. This paper presents an overview of the evolution of NIMIC: its concept formulation in NATO AC/310, its Pilot phase years, and the Center as it exists today.

These introductory comments are followed by an in-depth discussion of the following: the NIMIC management structure including its Steering Committee function; the input, content and maintenance of information in the database; the background and technical expertise of the staff of munitions experts; the analytical capability of the NIMIC in providing support to the munition design community in areas of insensitive munitions and safety; and the procedures by which one may request NIMIC technical assistance.

LIST OF ACRONYMS

AGARD	Advisory Group for Aerospace and Development
BRS	Bibliographic Retrieval Services

CNAD	Conference of National Armament Directors
CPIA	(U.S.) Chemical Propulsion Information Agency
DOD	(U.S.) Department of Defense
DOE	(U.S.) Department of Energy
DRIC	(U.K.) Defence Research Information Center
DSIS	Defense Scientific Information Service
DTIC	(U.S.) Defense Technical Information Center
IHEP	Insensitive High Explosives and Propellants
IM	Insensitive Munitions
MAS	Military Agency for Standardization
MoU	Memorandum of Understanding
NATO	North Atlantic Treaty Organization
NDRE	Norwegian Defence Research Establishment
NFPO	National Focal Point Officers
NIMIC	NATO Insensitive Munitions Information Center
NSTIS	NATO Scientific and Technical Information Service
NTIS	(U.S.) National Technical Information Service
TIP	Technical Information Panel (an AGARD task group)

1. WHY NIMIC?

All of us here may have the impression that we are dealing with a new problem called "Insensitive Munitions". Actually, we are only seeking new solutions to an old problem which has already caused many dramatic accidents.

In 1911, in France, gunpowder accidentally caught fire aboard the battleship LIBERTE, which exploded and sunk causing the death of 226.

In 1944, in Britain, in an RAF underground storage, workers accidentally caused an explosion which destroyed 3,500 tons of bombs and caused the death of 68.

In 1967 aboard the aircraft carrier USS FORRESTAL, a rocket accidentally started from one of the aircraft and initiated a fuel fire which propagated to other aircraft and munitions, causing the loss or damage of 64 aircraft and the death of 134.

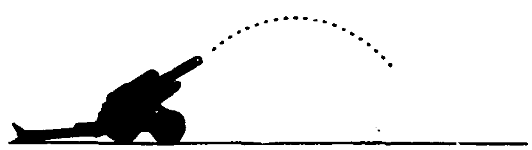
These are only a few among the many accidents which have occurred with munitions in the whole world (even regardless of wartime events due to enemy action), and which led the munitions community throughout the world to strive for less sensitive munitions.

Now, explosives will never be chocolate, and this is not what we want them for: what we need on the battlefield is not Easter eggs nor even plaster grenades. Insensitivity is not a purpose as such: the real purpose of a munition is efficiency. You can easily count how many casualties an ammunition accident costs; you cannot count explicitly how many casualties a lack of efficiency costs, but it does. From my personal experience, I know that zero risk does not exist on the battlefield, but that zero efficiency is one of the major risks. Hence you don't want to pay too much for insensitivity in terms of lack of efficiency.

Now, if your munitions are too sensitive, you don't even need an enemy to kill you: you will do it by yourself, even in peacetime. In that case, insensitivity is no longer in competition with efficiency: it becomes a contribution to efficiency.

Hence the rationale for IMs: we all want "more bang for the buck", but only at the other end of the trajectory.

The rationale for :
- **MURAT (MUnitions à Risque ATténué)**
- **IM (Insensitive Munitions)**
- **LOVA (LOw Vulnerability Ammunition)**



More bang for the buck...

... but only at the other end of the trajectory

These considerations have led to an international approach to the problem under the auspices of NATO, and to an attempt for a joint definition of rules governing the design of safer munitions, though still efficient, whatever the name they are given:

- in English, LOVA (Low Vulnerability Ammunition) or IM (Insensitive Munitions), although the adjective "insensitive" is certainly exaggerated;

- in French, MURAT (Munitions à Risque Atténué).

This international approach has resulted in the creation of NIMIC, i.e. the NATO Insensitive Munitions Information Center. The purpose of this paper is to describe how the NIMIC concept came out, what Pilot NIMIC has achieved, what NIMIC is currently doing and what it expects to do in the future.

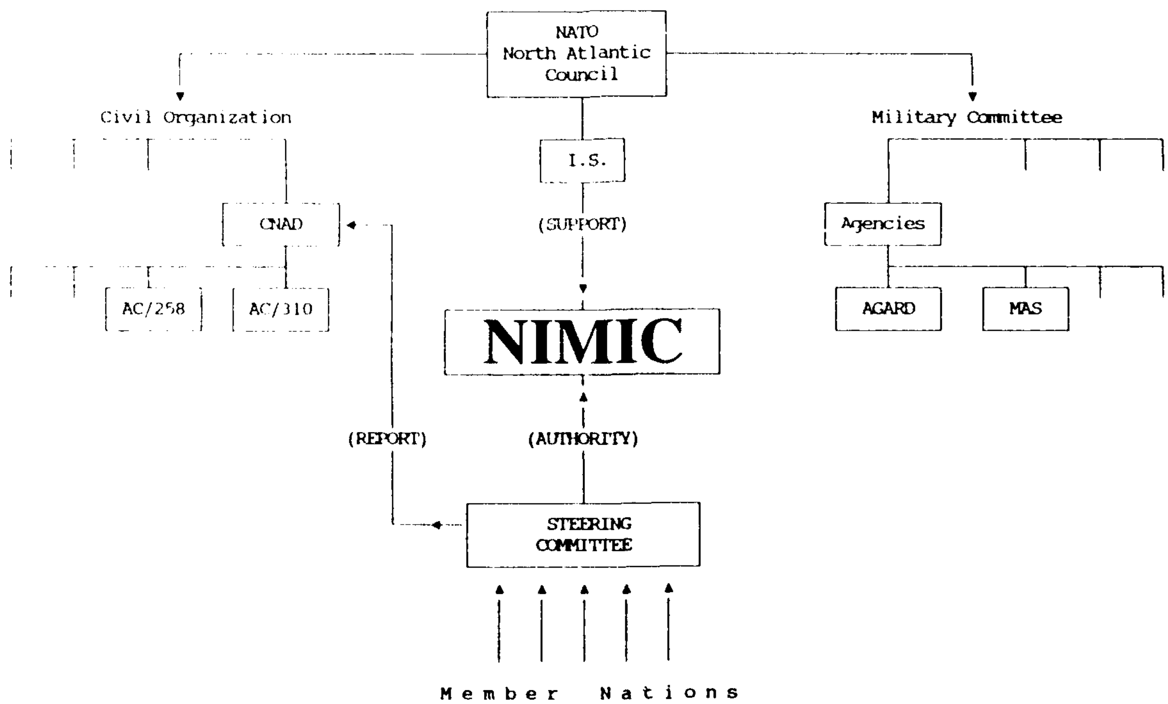
2.NIMIC WITHIN NATO

2.1 Position

To provide a frame of reference in understanding NIMIC and its functions, Chart 1 presents a simplified organizational structure for NATO. Indicated are the two major sides of the house, namely the civil and the military organizations. To these must be added the International Staff (IS) which provides support to all groups, committees and agencies. Only those groups and agencies of prime significance to NIMIC have been listed in this chart, for clarity.

On the civil side, the main group of interest is the CNAD (Conference of National Armament Directors), to which the NIMIC Steering Committee reports annually. Under CNAD are Army, Air Force and Navy Armament Groups, the Industrial Advisory Group and the Defense Research Group. Also under CNAD are several cadre groups which are basically multi-service (Army, Navy and Air force) in

Chart 1



nature, among them two groups specifically devoted to munitions:

- AC/258, involved with safety aspects of transportation and storage of ammunition and explosives, and

- AC/310, involved with safety and suitability for service of conventional munitions.

On the military side (i.e. under the Military Committee), we find military commands, and also agencies, among them:

- the Military Agency for Standardization (MAS), and of course

- AGARD.

2.2 NIMIC and AGARD

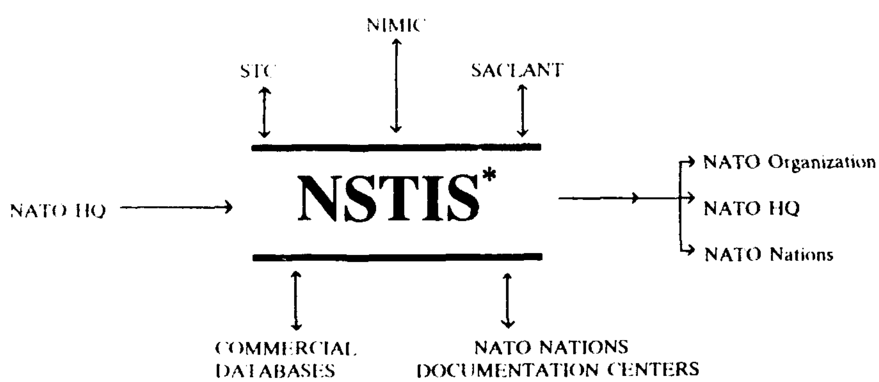
The relations of NIMIC with MAS are essentially devoted to the preparation of STANAGs, i.e. standardization agreements. The relations with AGARD are of a more technical nature.

Within AGARD, the panel most obviously related with NIMIC is Propulsion and Energetics, the organizer of this meeting. Now, NIMIC is also interested in the activity of the Technical Information Panel TIP. Indeed, as an aside, AGARD tasked TIP to address the need for a central repository for all NATO scientific and technical Information. As a result, TIP summarized the problem of NATO information as follows: "Scientific, Technical and other information (STI) generated by NATO is not fully utilized because it is not readily identifiable, retrievable or available to NATO staff and the nations, thereby causing great waste of time and resources" (Ref. 1)

This concern of AGARD TIP covered the total spectrum of information available in NATO, and a study group developed a concept for a NATO Scientific and Technical Information Service (NSTIC) (Chart 2). The proposed concept (Ref. 1) outlines a centralized, automated, information service performing the function of acquisition, selecting, cataloging, information retrieval and document ordering. It has always been intended that, should NSTIS become operational, NIMIC would be a sub-set group interfacing with it.

Chart 2

Interaction of NIMIC With The AGARD STIS



*NATO Scientific and Technical Information Service

2.3 NIMIC and AC/310

Now, the main link for NIMIC within NATO is with AC/310, where NIMIC was conceived to some extent, although NIMIC itself is a separate and distinct entity.

AC/310's full name is "Group on Safety and Suitability for Service of Munitions and Explosives". It was formed in 1979 to address the problem identified by CNAD as a major impediment to munition interoperability within the Alliance, specifically, the lack of an agreed safety assessment process.

In 1984, AC/310 became aware of the increased concern being voiced by nations regarding the vulnerability of launch platforms and storage sites as a function of the reaction of munitions to combat-induced environmental forces. Due to these concerns, the criteria for acceptance of munitions as safe and suitable for service, as stated in resulting national insensitive munition programs, were being stated in more stringent terms. AC/310 noted that, without the knowledge and availability of new technology, the task of munition designers in meeting these criteria while retaining operational effectiveness - which remains the primary goal of munitions - was becoming increasingly more difficult.

This is how AC/310 identified the need for a focal point within NATO to exchange Technical Information on Insensitive Munitions (IM) to facilitate design efforts in meeting the new and evolving IM requirements. This identified need then led to a series of actions initiated in AC/310, leading to the formation of NIMIC.

Chart 3 summarizes the main three phases of this formation:

- from 1984 to 1986, a number of intermediate steps toward the concept of an IM group,
- in 1988, the creation of a Pilot NIMIC in the United States under a 5-nation MoU,
- in 1991, the transition from Pilot NIMIC to NIMIC and its transfer to the NATO Headquarters in Brussels.

Chart 3

NIMIC History

1979	Creation of AC/310	
1984	US (initiative)	Concept of an IM Group
↓	FR (Chairmanship)	
	NL, NO	
1986	UK (workshop)	
1988	Creation of Pilot NIMIC (USA)	
1991	Transition to NIMIC (NATO HQ) (CA, FR, NL, UK, US)	

3. NIMIC HISTORY

3.1 Steps to Pilot NIMIC

The initiative for promoting the IM concept originated in the United States, involving both Departments of Defense (DOD) and Energy (DOE), the main promoter being the US Navy, which paid a heavy tribute to sensitivity in the last decades. An Insensitive High Explosives and Propellants (IHEP) study was conducted to increase the safety and survivability of munitions. This program was given additional impetus by a Joint Technical Coordination Group to improve munition survivability.

Ideas developed in these studies were presented to international and NATO audiences by the U.S., and support in a number of nations was evidenced. Virtually concurrent with the U.S. Program, both France and the United Kingdom launched efforts in the area of interest, focusing mainly on energetic material development or use.

The NATO group AC/310 formed several ad-hoc groups to validate the need for a center for IM technology exchange and to determine a logical location within NATO.

This study started under French chairmanship, and culminated in a workshop held in 1986 in London, which provided a forum for potential users to assess the value of such a center. The workshop was attended by 70 representatives of national government and industrial agencies, as well as various NATO groups from CNAD and MAS, including the Service Armament Groups.

The workshop resulted in a consensus that an Insensitive Munitions Information Center, with an analysis capability, would be of value. The Center should develop and maintain a data base of scientific and technical information, and be staffed by technical personnel to interrogate and analyze the data base to respond to technical questionnaires.

Since the need was immediate, the U.S. proposed a Pilot Center be established to meet the current need and plan for the establishment of the permanent NIMIC. A Memorandum of Understanding (MoU) was signed in May 1988 by France, the Netherlands, Norway, the United Kingdom and the United States. Canada joined by an Amendment to the MoU in April 1989.

The core staff of Program Manager, Systems Administrator, Technical Writer, Legal Consultant, and Secretary were provided by the Pilot NIMIC host country, i.e. the United Sates. Technical staff members were provided by secondment from the participating nations. Overall administration was provided by a Steering Committee composed of a representative of each participating nation, and chaired by the U.S. Representative.

The Steering Committee agreed that the efforts of Pilot NIMIC in performing the tasks identified in the MoU would be assessed prior to the establishment of the permanent NIMIC. An assessment report was written (Ref. 2), which was staffed within all participating nations. The report states in its synopsis: "In May 1988 a Pilot NIMIC program was established with the object of determining whether the NIMIC concept is viable. This report provides the evidence on which is based the conclusion that implementation of the NIMIC concept is capable of achieving the desired objective". The result of national staffing was a consensus that a permanent NIMIC should be formed.

4. NIMIC Organization

4.1 Status

Another MoU was executed on 24 October 1990 establishing a permanent NIMIC. Original participants are Canada, France, Netherlands, United Kingdom and United States. Prior to this, a letter of agreement was signed on 24 September 1990 by the Steering Committee and NATO regarding the provision of services and facilities by NATO in support of the NIMIC project.

Total funding of NIMIC is provided by the participating nations on a share basis, wherein large nations pay two shares and smaller nations one share. NIMIC operates under a budget approved by the Steering Committee, with NATO administering all financial matters, including the establishment of a NIMIC account in a NATO approved commercial bank.

Security is governed by a NIMIC Project Security Instruction which was developed to provide protection of classified information up to and including "Confidential", in accordance with national laws and regulations provided such are no less stringent than the NATO Security Document C-M(55)15(Final) of 31 July 1972. NATO will provide physical security for the NIMIC facility in accordance with normal NATO procedures.

4.2 Staff

Unlike Pilot NIMIC, the total staff for NIMIC is being hired in accordance with NATO hiring procedures. While the staff members are NIMIC employees, all personnel matters are processed in accordance with NATO procedures. Staff

NIMIC Operation

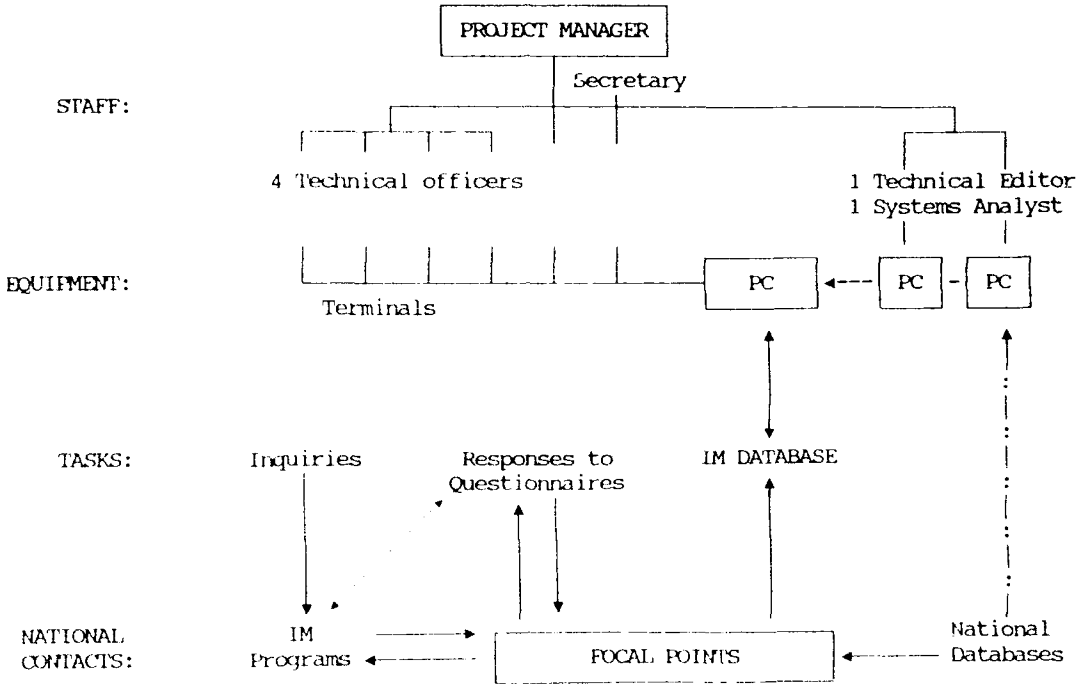


Chart 4

performance is assessed by the Steering Committee.

This staff is presently defined as shown in Chart 4:

- a program manager, with a secretary,

- four technical officers, each one specialized in a given field, i.e. Explosives, Explosion effects, Warheads design and Propulsion design,

- a technical editor and a systems analyst, more particularly in charge of the database and the computer equipment.

This amounts to 8 staff members, to be hired among candidates belonging to the participating nations. Unfortunately, the NATO hiring process is very lengthy, due to the obvious security requirements and to the inevitable political considerations to be taken into account. Hence the theoretical staff of 8 is still far from being completed today, which temporarily reduces NIMIC's efficiency. The transition from Pilot NIMIC to NIMIC certainly was a necessary step, but it is a difficult one, and the full working pace will only be attained in early 1992. NIMIC will then resume and expand the tasks identified in both the Pilot NIMIC and NIMIC MoU documents.

5.NIMIC's tasks

5.1 Links with Users

These tasks can be listed under three headlines (right to left on Chart 4):

- maintaining a specialized database,

- responding to questionnaires issued by member nations, and

- performing inquiries of its own.

All these tasks imply the existence of formal links with the users. To this end, each participating nation has provided NIMIC with a contact within the nation, a National Focal Point Officer (NFPO), who assists in efforts to input data and process questionnaires. Also each participating nation has identified national governmental agencies authorized direct contact with NIMIC. Any questionnaire from these agencies can be received and responded to directly by NIMIC. Other agencies and industrial concerns are to forward questionnaires to NIMIC via the appropriate NFPO, whose responsibility it is to validate, from an administrative view, the need for the assistance being sought. NIMIC responses will also be sent via the NFPO unless stipulated otherwise.

Other NATO groups (such as the Service Armament Groups) and other NATO nations can submit questionnaires to NIMIC via the Steering Committee. The authorization of the Steering Committee is necessary since many NATO groups have nations in membership which are not participants in NIMIC. The SC, if in unanimous agreement to provide the service, will forward the questionnaire to NIMIC for response. Assistance provided to non-participants will be subject to payment of a fee for services, based on the complexity of the effort involved.

5.2 IM Database

As far as the database is concerned, NIMIC's tasks are the following:

- collect, store and disseminate scientific and technical information on IM;

- provide and maintain a comprehensive data collection so as to facilitate design efforts for IM and minimize the cost of research and development efforts;

It is important to note that, even at this level, NIMIC already provides an analysis function for the selection of relevant documents, a characteristic which differentiates it from other "information centers".

Collection and selection of information can be effected through two different channels:

- the main one utilizes the NFPO to conduct searches for relevant information in national agencies;

- an optional channel is direct interrogation of national databases by means of a MODEM.

The main agencies and databases of the member nations are listed in Annex A. But this is not to say that the NIMIC database precludes entrance of information from non-participating nations. To the contrary, a significant amount of data from non-participants resides in NIMIC having been either volunteered by such nations or accessed from open literature.

In September 1991, these searches had already resulted in the review of more than 30,000 technical abstracts for relevancy to NIMIC. Of these, about 60 percent were considered relevant. In addition, over 7,000 hard copies of documents were received and a review indicated over 95 percent relevant for entrance into the NIMIC database. These searches will be a continuing effort of NIMIC to provide input to the database in as timely a manner as possible.

Information has been received in basically two forms: hard copy and floppy discs. All relevant information is processed for entrance into the IM database (machine searchable). Obviously it is of an advantage to NIMIC to receive the information in floppy disc or magnetic tape form, which aids not only in timely processing as machine readable, but also in reduction of storage space.

Once the information is converted to machine readable form, it is then placed in Bibliographic Retrieval Services (BRS)

Search format. BRS Search is a text-based database system residing on the hard disc of a compaq Deskpro 386 (IBM compatible) computer with backup onto two magnetic tapes. BRS Search is used extensively to query the databases listed in Annex B.

5.3 Responses to Technical Questionnaires

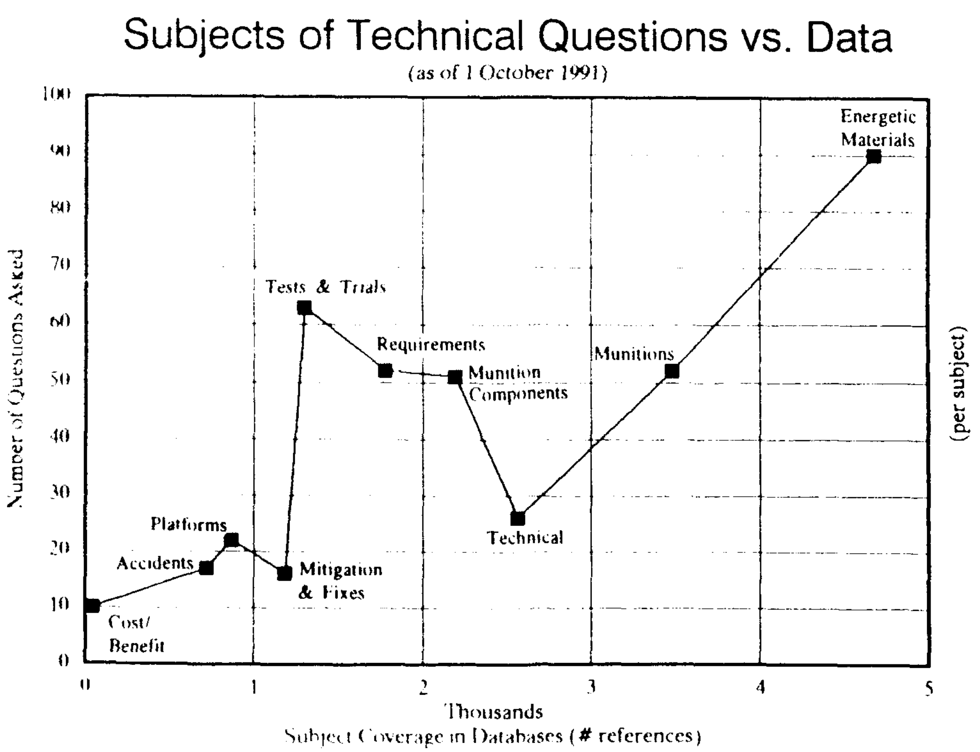
The principal objective in establishing NIMIC is to provide a NATO central point for the exchange of technical information in order to facilitate the design of munitions to meet national and future NATO IM requirements. While the term "insensitive munitions" is defined somewhat differently by nations, the general goal of reducing vulnerability of launch platforms and storage areas while retaining combat effectiveness is generally accepted by all. The goal is seldom achievable by a single approach, but requires the combination of several technologies (e.g. energetic material selection in conjunction with mitigating devices).

In all instances, the synergistic effects of the technology or technologies being proposed for application require consideration at a systems level. It is counterproductive to prevent a hazardous condition that arises infrequently in a combat situation and create a highly likely hazard in other phases of the logistic cycle. NIMIC was created to provide a source of information for the assessment of all factors involved in arriving at a design solution.

In the early months of Pilot NIMIC, the majority of questionnaires were factual in nature, not requiring much analysis or presentation of opinions and recommendations. In recent months, the questionnaires have been more searching in nature, and thus more in conformity with the plan for NIMIC. Chart 5 lists the activity of NIMIC in this area. It is evident from the number of questionnaires submitted that pilot NIMIC was recognized in the munitions community, and that this community is now anxious for assistance from NIMIC.

A comparison of the types of information in the database versus the subjects of questionnaires is presented in Chart 5. Not surprisingly, this chart indicates heavy emphasis in data input and questionnaires related to energetic materials. As time

Chart 5



progresses and the requirements for IM (nationally and in NATO) become better defined, the questionnaires to NIMIC will reflect the complex nature of design problems in meeting IM requirements, and will require an expanded database and the concerted efforts of the technical staff.

5.4 Inquiries and Studies

Last but not least, NIMIC will develop an activity of its own (although obviously along the lines defined by the Steering Committee) in order to anticipate the needs of the Member nations prior to future questionnaires. To this end, as its staff of technical officers is gradually completed, it will utilize its expertise for the following tasks:

- analyze technical requirements for IM, and assess methods and systems for improving IM to meet these requirements;
- recommend solutions or design approaches to meet IM requirements;
- identify technology deficiencies that prevent requirements from being achieved, and make proposals for remedial actions; and
- analyze data provided to NIMIC, and prepare data books and state-of-the-art reports on IM.

Indeed, through database interrogations to respond to questionnaires, NIMIC may identify technology deficiencies in its database in a given technology area. Such a deficiency can be indicative:

- either simply by a lack of data input by participating nations;
- or by lack of data having been developed in that given technology area.

NIMIC, as a first order of business, upon identifying a deficiency in its database, will contact participants, requesting (and aiding when possible) in the conduct of an in-depth search of national databases. Should the in-depth search of the specific technical area prove fruitless, then the deficiency obviously is due to a lack of existing data.

NIMIC, in such a situation, develops a proposal for a program to be undertaken as a collaborative venture to correct the deficiency. Current national budgetary constraints make collaborative ventures more than ever desirable and even necessary. Some specific areas identified by NIMIC as potential for collaborative programs are:

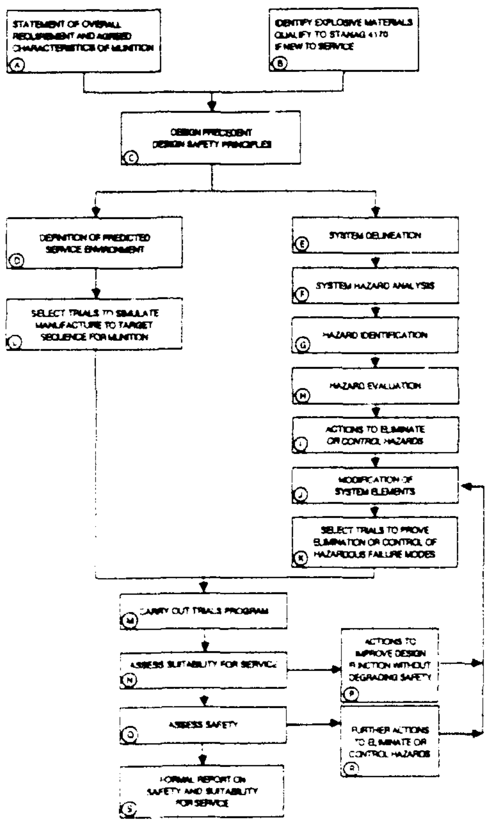
- analyzing the interest of some novel explosive molecules for IM;
- assessing IM insensitivity tests in order to get a better scientific understanding of the real phenomena occurring within the munition tested;
- developing reliable small scale or math model predictive tools;
- designing means to prevent or reduce the potential for sympathetic detonation in mass use munition storage configurations.

6. NIMIC AND THE IM PROCESS

6.1 Munition Assessment Process

AC/310 published AOP-15 "Guidance on the Assessment of the Safety and Suitability for Service of Munitions for NATO Armed Forces" (Ref. 2), and summarized the assessment process in Chart 6. While not specifically addressing the IM aspect of munition design, the same philosophy and methodology applies to assessing a munition to IM requirements as for safety requirements. Therefore, the subsequent comments will treat the two disciplines as one.

Chart 6



AN OUTLINE ASSESSMENT PROCESS

AC/310 agrees that the achievement of IM program goals can best be accomplished if IM characteristics are designed into the munition, and efforts to accomplish this should be initiated at the beginning of the munition development program. In cases where lack of technology, impact on performance, cost, etc., prohibit achievement of IM requirements through design, solutions should be sought by providing safeguards or protection to the munitions.

Within Chart 6, we will now put emphasis on those steps where NIMIC is capable of providing assistance to the design agent, as progress is made through this process.

6.2 NIMIC's Role Within the Process

NIMIC's assistance can be sought from the very beginning of the process, i.e. Steps A, B and C, where NIMIC can provide:

- input regarding current national and NATO IM requirements;

- advice and assistance in selecting adequate explosive and propellant materials; and

- information from accident and incident data on the past history of designs similar to that proposed, so that known pitfalls can be avoided.

Further down in the process comes Step I. The need for support in this step reflects the basic purpose for establishing NIMIC. In this area of recommending actions to eliminate or control hazards, NIMIC will utilize its database and the expertise of its staff to the fullest extent.

NIMIC assistance is also available through this design process in Steps L and K (involving the selection of tests and test parameters to validate that the design does in fact meet IM requirements).

It might be even more necessary in Steps P and R, which have an added degree of complexity in that any remedies suggested more than likely will be of a retrospective nature to an already existing design.

In order to cope with these tasks, the staff of NIMIC, though small in size, is composed of personnel who, as a group, have experience in total munition design (Energetic Materials, Warheads, Propulsion Units, Fuzes and Safe-Arm Devices, and Explosion effects). Albeit that the NIMIC data, as with any database, will always be expanding and will lag timewise behind the most recent technological developments, access to these recent developments is available to NIMIC. Indeed, one of the NIMIC sub-databases is the PCDB, or Points of Contact Database. This contains a listing of several hundred technologists in participating nations who have indicated a willingness to assist the NIMIC staff.

In instances of lack of information in the NIMIC database and/or lack of experience in a given subject by the staff, appropriate points of contact will be solicited to assist in identification of any new unreported technological advances.

Assistance of this nature, sought from nations by NIMIC, will be solicited to assist in identification of any new unreported technological advances, and will be governed by the NIMIC Security Guidelines established and agreed by the nations.

7. FUTURE

NIMIC is a project functioning within NATO. It is actively solicited for assistance by other NATO entities and even by non-NATO nations. At the same time, it is actively soliciting participation by all Alliance nations.

NIMIC, in these early months of NATO operations (as in its Pilot phase), has placed emphasis on IM considerations. However, recognizing the relationship between safety and IM concerns, NIMIC plans to expand its database to encompass safety as well as IM information. This expansion is necessary to allow full assessment of the synergistic effects of proposed remedial actions.

Now, NIMIC is also solicited by other NATO entities to expand its database and the activity of its technical staff to other areas within the munitions field. If this is accepted, a balance will have to be defined between:

- on the one hand, the interest for NATO of making the best possible utilization of the role of expertise represented by NIMIC, and

- on the other hand, the need for NIMIC to retain its primary mission in the IM field.

Even within the field of IM, as previously indicated, any assistance from NIMIC to NATO as a whole - or to non-participating nations - can only be sporadic in the present situation, where NIMIC is only funded by the participating nations. This is why NIMIC advocates the active participation of other nations.

Full national participation will provide many advantages such as:

- improved cost-effectiveness of operating the Center;

- expansion of the database; and

- higher potential for achieving munition interoperability in the Alliance.

Many lessons have been learned during the Pilot Phase regarding both administrative and technical aspects of operating an information center of this magnitude. NIMIC will continue to learn and grow in its ability to cope with future problems both administrative and technical as they arise.

In the near term, NIMIC will be engaged in a vigorous campaign to inform the technical community of its presence in NATO and its capability to serve their need. You, as members of this technical community, can assist NIMIC within your influence and also pass on to the NIMIC staff suggestions for improvement.

NIMIC will function as a team member with the national and NATO munition developers and desires that a spirit of cooperation permeates all of our mutual endeavors.

References

1. Advisory Group for Aerospace Research and Development (AGARD) - Technical Information Panel (TIP), "Proposal to Establish a NATO Scientific and Technical Information Service" (NSTIS), AGARD Report No. TIP/WG-01/NATO, AGARD HQ, Paris, France, April 1986.

2. NATO Insensitive Munitions Information Center (NIMIC) - "An Assessment of Pilot NIMIC", NIMIC-ESN-371-90 of 20 April 1990.

ANNEX A

National agencies and databases contributing to the NIMIC IM database

Canada

- Defence Scientific Information Service (DSIS)

France

- CEDOCAR

Netherlands

- Prins Maurits Laboratory/TNO

Norway

- Norwegian Defence Research Establishment (NDRE)
- Norwegian Defence Industry

United Kingdom

- DRIC
- IRS Dialtech
- HSELINE

United States

- National Technical Information Service (NTIS)
- Defense Technical Information Center (DTIC)
- Local databases such as those maintained for NASA, Chemical Propulsion Information Agency (CPIA), World Patent Index, etc.

ANNEX B

Breakdown of the NIMIC IM Database

- IMDB (IM DATABASE) - Nomenclature for the function allowing simultaneous search of the major subset databases

- NIDB (NIMIC Informational Database) - Main database containing bibliographies of technical reports. All documents entered are in hard copy NIMIC files.

- STANAG - Contains NATO (particularly AC/310) Standardization Agreements.

- JADB (Journal Articles Database) - Contains articles from technical periodicals.

- PTDB (Patent Database) - Contains Munition Related Patents (Worldwide).

- PCDB (Points of contact Database) - Contains listing of individuals in participating nations available to assist the NIMIC Technical Staff.

- CPDB (Company Database) - Contains information of the capability of industrial agencies for testing, analysis, etc.

- AXDB (Accident Database) - Contains information on munition related accidents.

- QSUM (Questionnaire Database) - Contains a compilation of questions referred to NIMIC.

PROGRESS AND INITIATIVES TOWARDS A UK INSENSITIVE MUNITIONS POLICY

by

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Summary

The UK view on the reasons for establishing an Insensitive Munitions policy and the difficulties in doing so are discussed. Recent MOD funded studies which throw light on the benefits of such a policy are considered. The organization being set up in the UK to support such a policy is described together with progress towards this goal.

Remark

The full paper is classified NATO confidential and cannot be included in this Conference Proceedings. If a reader is interested in more information on the subject he is asked to contact the author at the above address, or by

phone: 619-959 532222
or fax: 619-939 1413

Discussion

QUESTION BY WEISS, US: Please expand on the benefits part of the cost and benefits modelling. Does it take into account the cost of "unreliability" of the weapon system which would dictate more spares, more platforms, etc.? How about operational consideration whereby incidents due to a specified level of sensitivity less than satisfactory result in decommissioning of a platform or force stand-down while solutions are sought?

ANSWER: Ideally life costing of platforms using insensitive munitions should include all these effects if they are relevant. Indeed such costing would also normally include a period of wartime usage. However, I do not believe that the "unreliability" or "decommissions" aspects are currently being built into UK cost-benefit models.

FURTHER ANSWER BY MAWBEY, UK: The cost benefit analysis concerned with the benefits of introducing less-sensitive munitions on ships and submarines cover both peacetime and wartime scenarios. In the peacetime case the loss due to an accident is based on (a) the repair cost and (b) the potential loss in fighting availability due to the predicted damage. In the wartime case only

the potential loss in fighting capability resulting from a range of attack weapons is considered. The basic loss due to the accident/attack alone is compared with the loss due to: (a) the accident/attack with current munitions, (b) the accident/attack with munitions that meet BR8541 requirements, and (c) the accident/attack with munitions which meet the IMP requirement. Thus the net benefit of introducing less-sensitive munitions can be established. Comparing the benefit factored by the probability of the accident/attack occurring with the costs of introducing the less-sensitive munition contributes to the judgement which has to be made on safety policy. In the analysis it is assumed that an uncontrolled fire in a ship's magazine will lead to the effective loss of the munitions it contains.

QUESTION BY MOSES, US: In any intense conflict where resupply is difficult or too long in time, repairability becomes a very important term in the equation for availability. Explosions and fire almost always render a platform non-repairable and therefore unavailable; but repairable vehicles can often be returned in a few days (e.g. largely tanks during the 7-day war and the Yon Kipper war). This also has an impact on the maintenance and logistics requirements. Does your modelling take these benefits and costs into account?

ANSWER: Repairability and cost of repair is included in the UK whole life costing models. In a combat situation, a ship may not necessarily become unavailable after a minor fire and even tanks and aircraft might be more able to accomplish their immediate mission if the result of attack on an IM was no more that burning. However, repairability in order to ensure reuse of a platform during the same campaign is certainly a factor that should be built into combat availability models though it has not yet been taken account of in the UK modelling program.

SPECIFICATIONS ET CRITERES DE SECURITE DES MUNITIONS DESTINEES A LA MARINE FRANCAISE

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RESUME :

Apres avoir expose la genese des specifications et des essais de sécurite applicables aux munitions embarquees sur navires, des criteres d'acceptation sont presentes et compares aux normes en vigueur dans d'autres pays ou organisations.

Des evolutions possibles pour les annees a venir sont ensuite evoquées.

Enfin, d'autres approches complementaires a la securisation des munitions sont presentees.

INTRODUCTION

Un navire de combat rassemble dans un espace restreint de nombreux risques potentiels, parmi lesquels ses propres munitions embarquées constituent un facteur de vulnerabilite particulierement important, car elles peuvent initier des accidents ou en amplifier les effets

La Marine Française, comme la plupart des autres Marines, a toujours ete sensible aux problemes de securite de stockage et de mise en oeuvre des munitions à bord. Cette priorite s'est encore accrue a la lumiere des enseignements tires des engagements navals des dernieres annees, et d'accidents survenus à bord de bâtiments de combat modernes du monde occidental.

La methodologie retenue pour garantir un niveau de securite satisfaisant consiste à realiser pour les munitions des études de securite prenant en compte les differents environnements rencontres : normal, anormal et accidentel. Pour ce dernier, qui est le seul traite ici, les accidents les plus vraisemblables sont identifies, et des objectifs de securite leur sont associes.

Il est evident que les types d'accidents possibles dependent largement du navire porteur et des conditions d'emploi de la munition. C'est ainsi par exemple que l'environnement d'un missile destiné à un avion embarqué sera assez different de celui rencontre par une torpille de sous-marin, et qu'un certain degré de personnalisation des environnements accidentels s'impose.

De même, les criteres de securite varieront suivant que le potentiel explosif de la munition est plus ou moins eleve, que le navire est plus ou moins precieux, et que les conséquences d'un accident sont plus ou moins graves.

Neanmoins, dans le souci d'eviter les risques de personnalisation à outrance, il est apparu le besoin d'un cadre de reference : c'est l'objet des specifications d'essais et des criteres standards de securite. Dans la mesure ou les standards sont bien choisis, la personnalisation pourra rester relativement limitée, et reservée aux cas particuliers, qu'il s'agisse de la munition elle-même ou du navire porteur.

Les standards ont pour objet :

- de fixer un corps de doctrine, qui reste à moduler dans les cas particuliers,
- de servir de guide aux concepteurs de munitions,
- de couvrir le cas des munitions simples à usage très général,
- d'évaluer a posteriori le niveau de sécurite des munitions anciennes pour lesquelles il n'avait pas été établi initialement d'objectifs précis de sécurité.

Ils doivent être suffisamment ambitieux pour apporter un niveau elevé de sécurité, mais sans entraîner de surcoût excessif.

Ils doivent être également compatibles, autant que possible, avec ceux retenus par l'OTAN et par les Marines alliées pour faciliter l'interopérabilité. Une concertation permanente existe à ce sujet au sein du groupe AC 310 de l'OTAN "securité et aptitude au service des munitions et explosifs". Le NIMIC (Centre d'Information OTAN sur les munitions insensibles) constitue également une reférence interessante.

AGRESSIONS RETENUES PRIORITAIREMENT :

Les accidents imaginables, en temps de paix ou au combat, sont extrêmement nombreux, et il est necessaire de proceder à une analyse prealable pour retenir ceux qui sont les plus caractéristiques des menaces rencontrees.

C'est naturellement l'incendie, susceptible d'être rencontre en temps de paix ou comme conséquence d'une agression de combat, qui apparaît comme l'accident à prendre en compte en priorité, mais en distinguant deux types principaux dont les scenarios et les effets sont assez différents :

- l'incendie de bâtiment de surface, et plus particulierement de porte-aeronefs, dans lequel le carburant est un hydrocarbure brûlant en grande quantite avec un important apport d'air. Les temperatures sont elevees, et les durees peuvent être longues,

- l'incendie de sous-marin, dans lequel le carburant est plutôt une huile ou un fluide hydraulique, et où la quantite d'air disponible est limitee. Les temperatures sont beaucoup moins elevees, et les durées assez brèves.

Ensuite, l'accident de manutention apparaît egalement comme devant faire l'objet d'une grande attention. Il est admis que la chute de grande hauteur en est l'exemple le plus representatif. La hauteur de chute est generalement fixée à 12 m, le receptacle pouvant être plat ou dote d'obstacles pour simuler un effet de poinçonnement.

Une troisieme categorie comprend les agressions representatives de l'effet direct d'une agression de combat, sous la forme d'impacts de projectiles ou d'eclats, parmi lesquels on trouve :

- l'impact de projectile bassement energetique, modelise par une ou plusieurs balles de 12.7 mm perforantes,

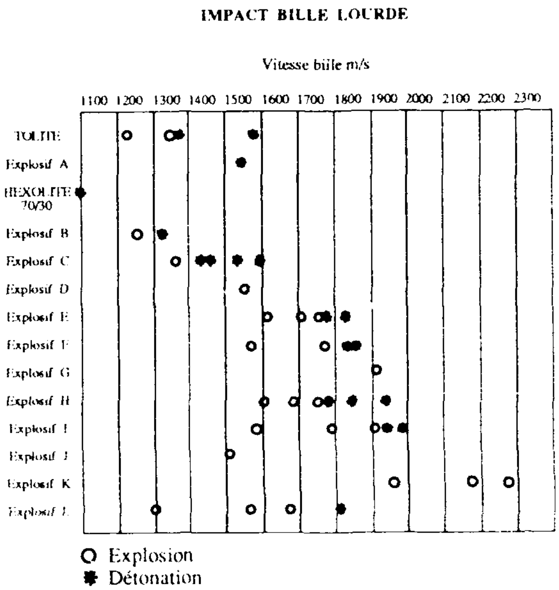
- l'impact d'eclat leger tres rapide, representatif d'un missile antiaerien, modelise par plusieurs eclats de faible masse atteignant simultanement la munition,

- l'impact d'eclat lourd, representatif de missiles antinavires ou de bombes, modelise par un seul eclat de masse plus elevee (par exemple, sphere d'acier de 250 g).

Eclat lourd : sphère d'acier de 250 g munie de son sabot de lancement

Cette derniere agression presente un grand interêt technique, car la mesure de la vitesse limite entraînant la détonation est un parametre tres discriminant. La procedure d'essai d'eclat lourd est largement utilisee pour caracteriser la vulnérabilité des nouveaux explosifs dans des maquettes elles-mêmes standardisees. Le tableau 1 présente quelques resultats.

Tableau 1



Une quatrième categorie regroupe les agressions representatives des effets secondaires d'un accident initial. On y trouve :

- la détonation par influence, qui permet d'evaluer le pouvoir amplificateur des munitions dans un accident, en tenant compte des configurations de stockage et du facteur aggravant apporte par le confinement,

- l'échauffement lent, qui peut representer l'effet à distance d'un incendie majeur de bâtiment de surface, avec un faible gradient de température et une longue durée. Cette agression présente également un grand interêt technique car elle conduit aux reactions les plus violentes de la munition en ambiance thermique,

- l'incendie de munitions, dans lequel la matiere combustible est un propergol ou un explosif. Les températures sont alors tres elevées, et les modes de réaction des munitions agressées sont encore peu connus.

Une dernière catégorie, qui n'est citee ici que pour mémoire, couvre les agressions d'origine électrique ou electromagnétique, comme la foudre, l'électricité statique, les rayonnements électromagnétiques continus ou impulsionnels. Elle ne sera pas développee ici

Le tableau 2 recapitule les specifications existantes ou en cours d'achevement.

Tableau 2

Liste des spécifications d'essais		
Reference	Titre	Date d'approbation
IT n° 9282-1	Echauffement rapide : . incendie type Bâtiment de Surface (BS) incendie type Sous-Marin (SM)	14-01-88
IT n° 9282-2	Impact de balle de 12,7 mm	28-02-88
IT n° 9282-3	Chute de grande hauteur	20-07-88
IT n° 9282-4	Impact d'eclat lourd	28-11-89
IT n° 9282-5	Detonation par influence	10-10-89
IT n° 9282-6	Echauffement lent	23-10-90
IT n° 9282-X projet	Impact d'eclat leger	En cours

CRITERES D'ACCEPTATION

Les munitions recentes font l'objet de specifications de securite, etablies en fonction du risque potentiel presente par la munition, de son environnement logistique et operationnel, et du type de navire ou d'aeronef qui les portent.

Il apparait que, pour des munitions d'une même generation, la demarche securite et la technologie disponible conduisent en general a des exigences similaires. Cette similarite est encore accrue chaque fois que l'on mene une etude d'ensemble pour la totalite de l'allocation en munitions d'un navire ; ceci est naturellement le cas pour les grands projets de navire comme par exemple le Porte-Avions Nucleaire Charles de Gaulle.

Au stade actuel, des criteres standard sont en cours de mise au point. Les grandes orientations sont les suivantes :

- incendie de bâtiment de surface : la reaction ne doit pas être plus violente qu'une combustion. Une exigence supplementaire est visee pour les munitions d'aeronefs embarquees sur porte-avions, a savoir : aucune reaction ne doit se produire pendant les premieres minutes de l'incendie.

- incendie de sous-marin : l'objectif est de n'avoir aucune reaction compte tenu de l'environnement particulier,

- chute de grande hauteur : il ne doit y avoir aucune reaction, avec possibilite de neutralisation de la munition pour enlèvement,

- impact de balle de 12,7 mm : l'objectif est de n'avoir aucune réaction, ou au maximum une combustion,

- impact d'eclat léger : l'objectif est de ne pas avoir de reaction plus intense que la combustion,

- impact d'éclat lourd : l'objectif serait de ne pas avoir de réaction plus intense que la combustion mais, compte tenu de la violence de l'agression, il pourra être accepte des réactions plus importantes sans toutefois atteindre le niveau de la detonation,

- detonation par influence : l'absence de detonation sera demandee,

Ces exigences, qui sont si besoin à moduler, constituent une base significative ; elles apportent un degré de securite suffisant pour qu'un accident de temps de paix ou une agression de combat ne soit pas amplifiee de façon excessive.

Bien que non entièrement figes, ces criteres peuvent constituer un guide utile pour les concepteurs de munitions, leur permettant de choisir les options techniques pour un large éventail d'applications presentes ou à venir.

Lanceur d'éclat lourd de 112,7 mm

COMPARAISON AVEC LES NORMES

ONU - OTAN - ETATS-UNIS - GRANDE BRETAGNE

La comparaison des normes françaises avec les normes etrangeres et internationales fait l'objet du tableau 3 : il est notamment fait etat des criteres d acceptation lorsque ceux-ci existent.

Les informations presentees proviennent de :

- ONU : division 1.6
- OTAN : STANAG 4325
- ETATS UNIS : MIL STD 2105A
- GRANDE BRETAGNE : BR 8541

La comparaison fait apparaître une forte convergence pour les principaux essais, et une parente certaine pour les criteres associes. Le groupe AC 310 de l OTAN favorise l'emergence d une doctrine commune.

Détonation de bombe soumise à l'échauffement rapide

Tableau 3

Pays organisation / Epreuves	ONU	OTAN	ETATS UNIS	GRANDE BRETAGNE	FRANCE
Impact balle (12.7 P)	Combustion	Combustion (recommandation)	Combustion	Pas de detonation Pas d explosion	Combustion
Echauffement rapide	Combustion	Combustion (recommandation)	Combustion	Selon specifications	1) Combustion(BS) 2) Non reaction(SM)
Detonation par influence	Pas de detonation	Pas de detonation (recommandation)	Pas de detonation	Pas de detonation	Pas de detonation
Impact d eclat leger		Combustion (recommandation)	Combustion		Combustion
Impact d eclat lourd					Pas de detonation
Echauffement lent	Combustion	Toute reaction doit etre notee	Combustion		Non specifie
Chute de grande hauteur	Non reaction	Non reaction			Non reaction

EVOLUTION DES AGRESSIONS ET DES CRITERES

Les agressions et les criteres presentes ci-dessus conduisent à concevoir des munitions presentant un niveau de risque attenue. Mais paradoxalement, un nouveau type d agression doit alors être pris en compte : l incendie de munitions.

En effet, les munitions à risques atténues, conçues pour brûler et non detoner lorsqu'elles sont soumises a des agressions du domaine accidentel, deplacent le probleme de la securisation du stockage en soute ou de la mise en oeuvre operationnelle des munitions. L'analyse des risques conduit desormais, pour les programmes d armement futurs, à prendre en compte les incendies de matieres explosives et de propulseurs pouvant degenerer en incendies generalises

A cet égard les capacites de lutte contre l'incendie (passives et actives) d'un bâtiment de surface ont une limite : en fonction de cette limite, des environnements thermiques maxima sont à l'étude.

Ceux-ci s'expriment en pratique par la notion de quantite maximale de munitions pouvant brûler sans mettre en cause la vulnerabilite de la soute, et par la notion de temps de reaction des munitions avec ou sans conteneurs soumises à des agressions thermiques de fort gradient de température.

La definition des criteres associes à ces exigences de securite depasse ainsi la formulation des premiers criteres, presentes precedemment.

D'autre part, la menace terroriste fait peser et va faire peser pendant le temps de paix et le temps de crise sur l'ensemble des nations et de leurs Marines en particulier un risque important : c'est ainsi que l'attaque terroriste type charge creuse impose que les effets du jet residuel soient fortement attenues et que la tenue des munitions futures a ce jet residuel soit etudiee.

Cet exemple illustre les nouvelles preoccupations issues de l'utilisation possible terroriste ou non des armes de combat terrestre contre les navires.

UNE AUTRE APPROCHE : PRISE EN COMPTE DE L'ENVIRONNEMENT

La technologie disponible dans le futur permettra la tenue des nouvelles exigences de securite associees aux nouvelles agressions et nouveaux criteres definis.

Celles-ci peuvent sembler aujourd'hui tres ambitieuses compte tenu de l'etat de l'art disponible en matiere de munitions a risques attenues pour des coûts acceptables.

Pour tenir les objectifs de securite des programmes, il est donc utile de rechercher des solutions complementaires d'amelioration des conditions de stockage et de mise en oeuvre operationnelle des munitions ; celles-ci passent par le durcissement de l'environnement même des munitions.

Cet environnement se decline selon trois niveaux :

- les conteneurs de munitions

- l'organisation du stockage

- la conception et l'amenagement des soutes.

Les conditions de stockage en soute de munitions conventionnelles embarquees sont considerees comme critiques si la reaction accidentelle d'une munition peut entraîner la detonation en masse des munitions voisines, voire la perte du bâtiment.

La definition de conteneurs securises est susceptible d'ameliorer cette situation. Des regles de dimensionnement ont ete etudiees : elles portent sur la recherche d'une configuration de stockage optimisee, sur la definition des distances minimales d'isolement a respecter entre munitions ainsi que sur les caracteristiques des ecrans a interposer.

Les resultats significatifs obtenus pour des munitions chargees en explosifs coules fondus permettent d'envisager, pour des explosifs moins sensibles, des protections type conteneurs et ecrans d'un devis de masse notablement allege.

D'autre part, la connaissance des effets des munitions soumises aux agressions accidentelles permet la realisation d'etudes de securite de stockage afin d'optimiser le plan de stockage des munitions et conteneurs embarques.

Enfin, la conception des soutes et leur securisation sont des composantes essentielles de l'environnement "munition".

La definition de barrieres de securite type blindage, protections thermiques, dispositifs d'evacuation des gaz ... contribue a cette securisation. La reflexion est menee au cas par cas en prenant en compte chaque couple soute/munition.

Ainsi ces trois actions subsidiaires contribuent au durcissement de l'environnement munition. L'integration des munitions à bord des bâtiments de surface a un niveau de securite satisfaisant passe egalement par ces voies d'etude elles-mêmes complementaires de l'effort realise en matiere de munitions à risques attenues.

En conclusion, la convergence entre les actions portant sur la securite intrinseque des munitions et celles portant sur le durcissement de leur environnement devrait permettre de deboucher sur des solutions techniques de moindre coût pour satisfaire les exigences de securite de chaque programme.

SAFETY SPECIFICATIONS AND CRITERIA CONCERNING MUNITIONS INTENDED FOR THE FRENCH NAVY

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ABSTRACT

After considering criteria of safety specifications and tests applicable to munitions carried on board navy ships, criteria of approval are examined and compared with standards in force within other countries and organizations.

Next are considered possible developments in years to come.

Lastly, further approaches concerning safety measures of munitions are discussed.

INTRODUCTION

A [illegible] in a limited space [illegible] which its [illegible] represent a [illegible] as they can [illegible] multiply their effects.

The French Navy, like many other Navies, has always been sensitive to the problems of storage and stowage of munitions aboard. This priority is increased still further in the light of experience drawn from naval engagements of recent years and from accidents which have arisen aboard modern fighting ships of the western world.

The methodology retained in order to guarantee a satisfactory level of safety involves carrying out safety studies on munitions and taking into account the different environments encountered: normal, abnormal and accidental. As far as the last of these is concerned and it is the only one dealt with here, the most likely accidents are identified and some safety objectives are identified with them.

It is clear that possible types of accident depend largely on the carrying vessel and the conditions under which the munition is used. Thus, for example, the environment applied to a missile intended for a seaborne aircraft will be rather different from that of a submarine torpedo, so some degree of tailoring of the accident environment becomes essential.

Similarly, safety criteria will vary according to whether the explosive potential of the munition is high or low, whether the ship is particularly valuable or not, and on the gravity of the accident.

Nevertheless, in order to avoid the risk of tayloring things to excess, it has become clear that a reference framework is needed : this is the aim of the test specifications and of the standard safety criteria. In so far as the safety standards have been well-selected, the tayloring may remain relatively limited and reserved for special cases - be it a question of the munition itself or of the carrying ship.

The objective of the standards is :

- to establish a general policy which may be adapted to suit the particular case concerned.
- to serve as a guide to the munitions designer.
- to cover the case of simple munitions designed for general use.
- to evaluate, a posteriori, the safety level of old munitions for which no precise safety objectives had been established initially.

They must be ambitious enough so as to provide a high level of safety, yet without entailing excessive costs.

They must be also compatible, as far as is possible, with NATO and Allied Navies standards in order to facilitate interoperability. A permanent dialogue exists on this subject within the NATO group AC 310 "Safety and Suitability for service of munitions and explosives". NIMIC (NATO Information Centre on Insensitive Munitions) also represents an interesting point of reference.

SELECTED AGRESSIONS :

Conceivable accidents, whether in peacetime or during a conflict, are extremely numerous and first need to be analysed to identify the most characteristic of the threats encountered.

Fire is the most likely accident to occur both in peacetime and during a conflict and so must take priority over the others, not forgetting to distinguish between its two principal types, each of which has different patterns and whose effects are rather different :

- fire aboard a surface ship and more particularly aboard aircraft-carriers, in which fuel consists of a large quantity of combustible hydrocarbon with a large proportion of air. Temperatures are high and the periods of time concerned can be long.

- fire aboard a submarine, where fuel is more usually an oil or a hydraulic fluid and where the quantity of available air is limited. Temperatures are not nearly as high and the periods of time concerned are rather short.

Next are the accidents which occur during handling and these deserve a fair amount of consideration. It is accepted that material falling from a great height is the most representative example here. Height of drop is generally fixed at 12 m, its landing place may be a flat surface or one equipped with obstacles in order to simulate a perforation effect.

A third category includes agressions repres[illegible] the direct effect of a combat agression [illegible]e form of projectiles impacts or fragmen[illegible], among which are found :

- Low-energy projectiles impacts [illegible]delled by one or several shots by 12,7 mm perfo[illegible]ating bullets.

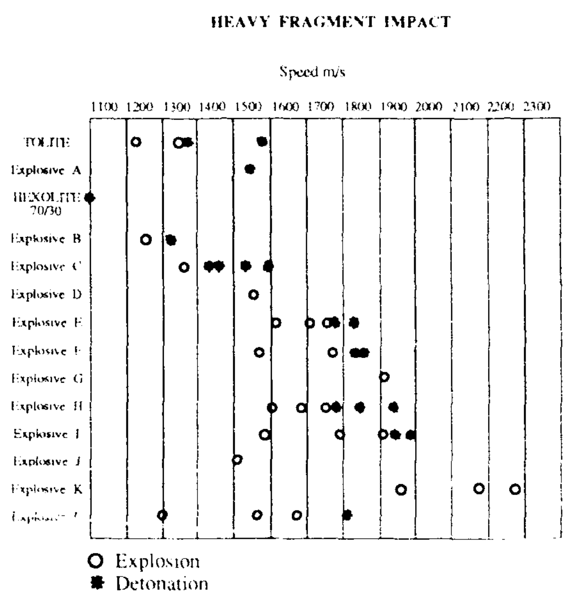
- very rapid light fragment impact from an anti-aircraft warhead modelled by one or several shots from low-mass fragment hitting the munition simultaneously.

- heavy fragment impact from anti-ship missiles or from bombs modelled by a single shot from a higher mass (e.g. 250 g steel sphere).

Heavy Fragment : 250 g. Steel Ball on its Launching Sabot

This last agression is of great technical interest, as the measuring of the maximum fragment speed leading to detonation is a very discriminating parameter. The heavy fragment test procedure is widely used to characterise vulnerability of the new high explosives in models which have themselves been standardised. Table 1 shows several results.

Table 1



A fourth category covers agressions representing the secondary effects of an initial accident. These include :

- sympathetic detonation, which allows for the evaluation of the amplifying power of munitions in an accident, whilst taking into account storage layout and the aggravating factor of the confined space,

- slow cook-off, which, with a low temperature gradient and over a long period of time, can model the effect of a major fire on board a surface ship. This agression is equally of great technical interest as it leads to the most violent munition reactions in thermal environment,

- munitions fire, in which the combustible material is a propellant or a high explosive. In such cases, temperatures are very high and the ways in which the affected munitions react are still little known.

One last category, only referred to here for the sake of completeness, covers agressions originating from electrical or electromagnetic sources ; such as lightning, static electricity, continuous or pulsed electromagnetic radiation. This category will not be developed here.

Table 2 summarises existing specifications or those in the process of being completed.

Table 2

List of the test specifications		
Reference	Title	Approval date
IT N° 9282-1	Fire : . type of fire surface ship . type of fire submarine	14th January 1988
IT N° 9282-2	12,7 mm Bullet impact	28th February 1988
IT N° 9282-3	Drop from a great height	20th July 1988
IT N° 9282-4	Heavy fragment impact	28th November 1989
IT N° 9282-5	Sympathetic detonation	10th October 1989
IT N° 9282-6	Slow cook-off	23rd October 1990
IT N° [illegible]	Light fragment impact	currently underway

ACCEPTANCE CRITERIA

Recent munitions are the subject of <u>safety specifications</u>, established in relation to their potential risk, their logistical and operational environment and the type of ship or aircraft carrying them.

For munitions from the same generation, safety processes and available technology generally lead to specify similar requirements. This similarity is further increased each time an overall study is carried out on the whole of the munitions allocation of a ship , this is naturally the case for large ship projects such as the Nuclear Aircraft Carrier Charles de Gaulle.

At this moment in time, the standard criteria are in the process of being finalised. The main trends are as follows

- fire on board a surface ship : the reaction must be no more violent than burning. A further requirement is intended for aircraft munition carried on board aircraft-carriers : no reaction must occur during the first minutes of the fire,

- fire on board a submarine : the objective is to have no reaction given the particular environment,

- drop from a great height : there must be no reaction, with the capability of neutralizing the munition for removal,

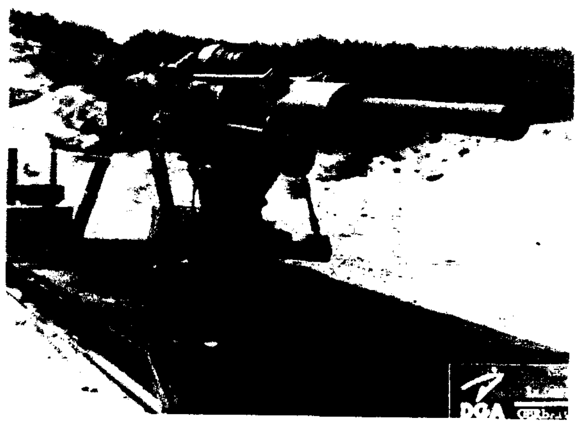
- 12,7 mm bullet impact : the objective is to have no reaction, or at the very most a burning,

- light fragment impact : the objective is to have no stronger a reaction than burning,

- heavy fragment impact : the objective would be to have no stronger a reaction than burning, but, taking into account the violent nature of the agression, stronger reactions may be acceptable as long as they do not reach detonation level,

- sympathetic detonation : there must be no detonation.

Although not entirely finalized, these criteria can from now on act as a useful guide for munitions designers, giving the opportunity of selecting technical options for a large range of present or future applications.



Gun Launching 112,7 mm Heavy Fragment

COMPARISON WITH UN - NATO - UNITED STATES - GREAT BRITAIN STANDARDS

Comparison of French standards with foreign and international standards is the subject of Table 3 : it notably sets out the acceptance criteria where appropriate.

Information presented originates from :

- NATO : STANAG 4325
- UN : division 1.6
- UNITED STATES : MIL STD 2105A
- GREAT BRITAIN : BR 8541

The comparison reveals a strong convergence for the main tests and a certain parity for the associated criteria. The AC 310 NATO group may encourage the emergence of a common policy.

Detonation of a Bomb under Fast Cook-off

Table 3

Country/organisation Test	UN	NATO	UNITED STATES	GREAT BRITAIN	FRANCE
Bullet impact	Burning	Burning (recommendation)	Burning	No detonation No explosion	Burning
Fire	Burning	Burning (recommendation)	Burning	According to specifications	1) Burning(Surf.) 2) Non reaction(S.M.)
Sympathetic detonation	No detonation	No detonation (recommendation)	No detonation	No detonation	No detonation
Light fragment impact		Burning (recommendation)	Burning		Burning
Heavy fragment impact					No detonation
Slow cook-off	Burning	Every reaction must be noted	Burning		No specified
Drop from a great height	No reaction	No reaction			No reaction

EVOLUTION OF AGRESSIONS AND CRITERIA

The above agressions and criteria have lead to the concept of less sensitive munitions However, paradoxically, a new type of agression must therefore now be taken into account munitions fire

In effect, the lower risk munitions, designed to burn and not to detonate when submitted to agressions of an accidental nature, modify the problem of safe storage in magazines or the operational applications of the munition As far as concerns future armement programmes, analysis of the risks from now on leads us to take into account fires of explosive materials and propellers which may degenerate in generalised fires

In this regard, the fire-fighting capabilities (passive and active) of the surface ship are limited ; with regards this limitation, maximum thermal environments are under study.

In practice, these are expressed by the idea of the maximum quantity of munitions which can burn without jepordising the vulnerability of the magazine, and by the notion of reaction time of munitions, whether containerised or not, and submitted to thermal attacks with a strong temperature gradient.

The definition of the criteria associated with these safety requirements thus goes beyond the drawing up of those first criteria formerly presented.

Moreover, threat of terrorism weighs heavily and affects all nations during both war and peacetime, representing a huge risk for navies in particular : that is why terrorist attacks of the shaped charge type imply that effects of the residual jet are greatly extenuated and that behaviour of future munitions in response to this residual jet has to be studied.

This example illustrates the new pre-occupations arising out of possible terrorist use of weapons designed for land combat against ships.

ANOTHER APPROACH : CONSIDERATION OF THE ENVIRONMENT

Technology available in the future will allow for respect of new safety requirements associated with the new types of agressions and with the newly defined criteria

All this may seem very ambitious today when state of the art available, in the matter of low-risk munitions at acceptable costs, is taken into account.

In order to fulfill safety objectives of the programmes, it is therefore useful to look for additional solutions to improve storage conditions and operational uses of the munitions ; the latter involving a hardening of the environment and even of the munitions

This environment declines at three levels

- Munitions containers
- Storage organisation
- Magazine design and layout

Storage conditions, in the magazines, of conventional munitions taken on board are seen to be critical if accidental detonation of a munition can entail the mass detonation of neighbouring munitions, and even loss of the ship.

Definition of securized containers is hoped to improve this situation. Rules for measuring up have been studied : they relate to the search for a configuration of optimised storage, to the definition of minimum isolating distances to respect between munitions and also to the characteristics of screens to be interposed

Significant results obtained for munitions carrying cast high explosives allows for consideration, in the case of less sensitive high explosives, of a container or screen form of protection made of a notably much lighter mass

Moreover, knowledge of effects of munitions subjected to accidental agressions allows for studies to be carried out on safety of storage in order to optimise storage layout of munitions and containers taken on board

Finally, design of the magazines, and making them safe, are essential components in the "munitions" environment. Definition of safety barriers in terms of screening, thermal protection, devices for the evacuation of gases ... contributes to these safety measures. Careful consideration is given to each case, taking into account which munition is put into which magazine each time.

Thus these three subsidiary actions contribute to hardening of munition's environment. If munitions are to be integrated at satisfactory safety-levels on board surface vessels, they have to equally undergo these study-processes, the studies themselves being complimentary to the work put into low-risk munitions.

In conclusion, convergence between actions relating to intrinsic safety of munitions and those relating to hardening of their environment, should allow technical solutions to be developed at minimum cost, in order to satisfy the safety requirements of each programme.

Discussion

QUESTION BY MAWBEY, UK: The Royal Navy requirement for the drop test is also that there should be "no reaction"; also the munition must be dropped from a credible drop height representative of service use. The sympathetic detonation pass criteria implies "explosion" is acceptable - should we not be seeking a response no more severe than burning or deflagration?

ANSWER: As I indicated to you in the presentation, that is not completely defined. However, I gave you a full orientation, concerning the criterion associated with the detonation. The announced objective is to not have a detonation of the receptor munitions: that is the minimum safety requirements; in fact, specifying such non-detonation implies a non-amplification of the initial accident. But as you suggested, in other reactions less severe than a detonation there is not less damage for the condition of the munition. In case of a specific naval program, we are bringing more specification of the reactions in which the level of severity is not more than a combustion.

QUESTION BY HELD, FRG: What was the weight and velocity of your light and heavy fragments?

ANSWER: The fragment velocity for the light fragment impact test is defined as follows: 200 m/s for three fragments of 4 gm mass each. For the heavy (250 gm) fragment impact tests the velocity specified is 1500 m/s. That velocity can evolve in case people criticize the testing conditions in Fin's evaluation of new pyrotechnic products.

LES TRAVAUX FRANCAIS SUR LES SUBSTANCES EXPLOSIVES POUR MUNITIONS A RISQUES ATTENUES (MURAT)

Formulation - Caracterisation - Prédiction du comportement

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1 - PREAMBULE

En France, les premières etudes concernant les MURAT ont été lancées et conduites par le Service Technique des Poudres et Explosifs (STPE) de la DGA.

La DGA est l'organisme du ministère français de la Defense chargé de :

- developper et acquerir les matériels qui correspondent aux besoins de l'armée française,

- veiller à la bonne santé des industries françaises de l'armement des secteurs étatiques, nationalisés ou privés,

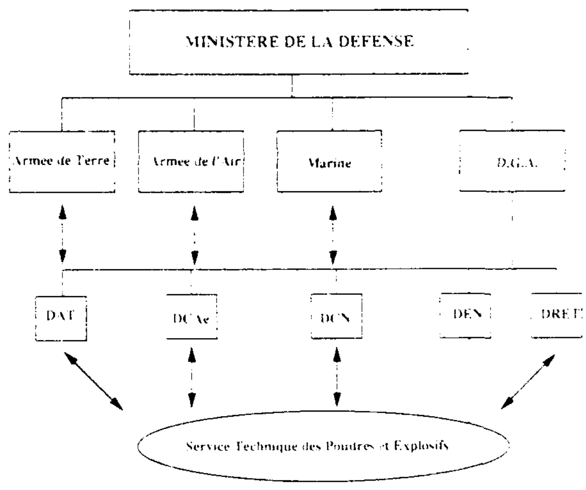
- développer les exportations d'armement

- produire certains equipements

Au sein de la DGA, le STPE est le service responsable des etudes de synthèse, formulation et développement des materiaux energetiques (poudres, explosifs et propergols).

Ces etudes sont effectuees en grande partie a la SNPE, mais aussi dans un certain nombre d'etablissement de la DGA pour ce qui concerne l'evaluation de leurs performances, securite, aptitude au service (GERBAM et GERPY de la Direction des Constructions Navales, ETBS de la Direction des Armements Terrestres, CAEPE et CEL de la Direction des Missiles et de l'Espace) et la comprehension des phenomenes de detonique mis en jeu (CEG et Institut franco Allemand de Saint Louis de la Direction des Recherches, Etudes et Techniques).

Situe entre les formulateurs, fabricants de produits explosifs et les maîtres d'oeuvre concepteurs de munitions et systèmes d'armes, le STPE est donc en quelques sorte le point focal français des problèmes liés à l'utilisation des substances pyrotechniques



2 - INTRODUCTION

La sécurité pyrotechnique est un souci permanent des concepteurs, des fabricants et utilisateurs de munitions. C'est un problème qui est traité depuis de nombreuses années et qui fait l'objet d'une réglementation très précise et très stricte (sécurité des travailleurs, au stockage, au transport...) (1). L'absence d'accident important en France depuis de nombreuses années démontre l'efficacité des mesures réglementaires ou des solutions techniques utilisées.

Cependant l'amélioration des performances des munitions se traduit souvent par un accroissement des risques qu'elles présentent ; leurs conditions d'emploi évoluent, et les menaces, particulièrement en temps de crise, augmentent. Il est donc primordial de rester vigilant et d'étudier toutes les solutions permettant de s'adapter à l'évolution des risques pyrotechniques.

Certaines solutions techniques permettent d'assurer aujourd'hui une sécurité satisfaisante :

- protections par des matériaux qui atténuent l'energie de l'agression initiale,

- cloisonnements qui ralentissent ou arrêtent la propagation du sinistre,

- disposition des munitions les unes par rapport aux autres et procédures d'utilisation,

- dispositifs d'intervention,...

Mais toutes ces solutions portent sur l'environnement externe de la munition. Les progrès technologiques de ces deux dernières décennies permettent maintenant de concevoir de nouvelles solutions pour diminuer les risques en agissant directement sur les matériaux explosibles et/ou sur les autres composants de la munition, et ont conduit au concept de MUnitions à Risques ATténués (MURAT en français, IM pour Insensitive Munitions en américain, ou LOVA pour Low Vulnerability Ammunition en anglais (2).

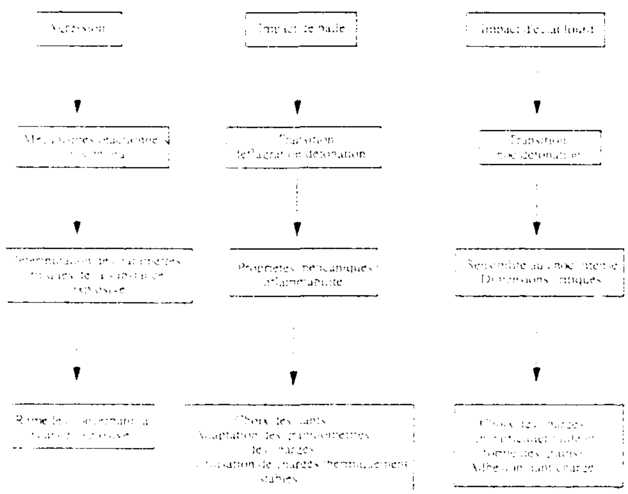
Ces risques pourront encore être réduits en particulier par des systèmes de déconfinement qui empêchent une réaction faible et/ou locale de dégénérer en réaction violente et/ou généralisée (structures bobinées ou métalliques spiralées en cas de surpressions internes, cordeaux découpants ou éléments de structure fusibles en cas d'échauffements), mais c'est principalement en agissant sur la substance pyrotechnique elle-même que l'on s'assurera du respect de ces labels d'immunité.

La difficulté consiste alors à réduire la réactivité des substances tout en conservant un niveau de performances compatible avec la mission de la munition.

3 - TRAVAUX EN FORMULATION

La mise au point de formulations moins vulnérables passe par une analyse des agressions et des mécanismes réactionnels que celles-ci mettent en jeu. On en déduit alors les paramètres critiques au niveau de la formulation, et les voies dans lesquelles la recherche doit s'orienter.

Exemples :



Les grands axes d'efforts pilotés en France par le ministère de la Défense pour les 3 grandes familles de substances explosives : explosifs, propergols, poudres pour armes sont brièvement indiqués ci-après :

3-1 Propergols pour autopropulsion

Les études sont axées sur 2 voies complémentaires :

- amélioration des caractéristiques de sécurité et de vulnérabilité des familles de propergols existantes
* en jouant sur le liant (taux, masse moléculaire, ...) et les charges (taux, granulométrie, ...)
* en recherchant des additifs qui diminuent la vitesse de combustion des propergols à pression atmosphérique ou qui diminuent la sensibilité de ces compositions aux agressions thermiques, à l'impact de balle ou à l'impact de fragments

Ces travaux concernent les butargols (propergols composites à liant polybutadiène) et les propergols à liants énergétiques (plastifiés par de la nitroglycérine et chargés en nitramines et/ou perchlorate d'ammonium).

- à partir d'éléments de formulation (liant, huile nitrée, charge) que l'on estime devoir présenter de bonnes caractéristiques de sécurité, amélioration des autres propriétés des propergols obtenus (performances, discrétion, propriétés mécaniques et balistiques, rhéologie, stabilité, ...).

Il s'agit ici d'utiliser des matières premières peu sensibles, notamment le nitrate d'ammonium à la place des nitramines et du perchlorate d'ammonium, associées à un liant basé sur un nouveau prépolymère énergétique (le PAG) non plastifié par de la nitroglycérine.

Toutes ces études de formulation se font en étroite liaison avec des travaux de méthodologie visant à comprendre les phénomènes entrant en jeu lorsqu'on soumet les chargements aux différentes agressions (analyse des phénomènes de transition en détonation, modélisation de l'effet des agressions sur les chargements et validation sur des essais instrumentés).

3-2 Explosifs de chargement

Les études de formulation sont menées en parallèle dans trois domaines :

* extension de la gamme d'explosifs composites à liant polymerisé fortement chargés en oxynitrotriazole (ONTA) grâce auxquels la détonation par influence de munitions (5,35 et 100 kg) est évitée (5) : augmentation du taux de charges, amélioration du vieillissement, introduction de nouveaux liants et plastifiants, formulations adaptées aux munitions peu sensibles devant procurer un effet d'éclat, de souffle, de relèvement ou aux blindages réactifs.

* étude théorique de l'enrobage des grains d'explosif pour compression et influence sur l'objet comprimé.

* diminution , grâce à l'introduction d'additifs, de l'inflammabilité (délai de réaction, vitesse de combustion) des explosifs à fort taux de charge en octogène et en hexogène.

Là encore, les études de formulation utilisent (ou servent à) des travaux de méthodologie visant à comprendre et améliorer les réactions des munitions (ou éléments de munition) les utilisant. On peut citer à titre d'exemple l'étude de l'influence de la granulométrie et du taux des diverses charges sur la vulnérabilité aux diverses agressions et les performances.

Enfin, du point de vue fonctionnement, la mise au point de nouveaux systèmes ou principes d'amorçage, d'une part à base de compositions elles-mêmes peu sensibles, d'autre part capables d'amorcer ces nouvelles formulations moins sensibles aux chocs, s'est également avérée nécessaire. Les résultats les plus intéressants ont été obtenus avec la mise au point de générateurs d'ondes de Mach.

3-3 Poudres pour armes

Les études concernent essentiellement des poudres sans nitrocellulose comportant une substance explosive, en général l'hexogène, et un liant.

Ces poudres dites composites constituent une transposition aux armes à tube des technologies développées pour propergols composites. Deux voies sont explorées simultanément, compositions avec ou sans solvant, et les travaux concernent :

- l'amélioration des propriétés mécaniques par optimisation du liant
- l'amélioration de l'allumage au moyen d'additif
- l'accroissement de la force par augmentation du taux de charge ou utilisation de liants énergétiques.

Parrallèlement à ces travaux concernant les substances sont effectués des évaluations en armes et des essais de vulnérabilité ainsi qu'une étude sur l'allumage de ce type de poudre.

4 - EVALUATION

4-1 Essais standards d'évaluation de la sensibilité

On retrouve principalement les épreuves préconisées par l'ONU pour le transport des marchandises dangereuses (épreuves des séries 1, 2 et 3) et en cours de standardisation au sein du groupe OTAN AC 310 :

- onde de choc
- impact
- friction
- décharge électrostatique
- échauffement

mais aussi des épreuves plus spécifiquement destinées aux substances ayant le label d'extrêmement peu sensibles (épreuves de la série 7 ONU pour MURAT) :

- sensibilité à l'amorce
- impact de balle
- friabilité dangereuse
- échauffements lents et rapides

Ces épreuves correspondent généralement à des stimuli élémentaires et permettrent de classer les produits de façon relative

Avantages

- épreuves peu coûteuses et donc possibilité d'une large banque de données.
- réalisables dès la mise au point des nouvelles formulations (peu de produit mis en jeu).

Inconvénients

- ne prennent pas en compte les effets de géométrie, masse et confinement
- la prédiction du comportement en munition n'est possible que de façon relative par comparaison avec les résultats obtenus sur des produits d'une même famille

4-2 Epreuves sur maquettes

Afin de prendre en compte l'influence de la géométrie, de la masse et du confinement des chargements sur la réactivité des substances explosives, la France a lancé depuis un peu plus de 5 ans la réalisation d'épreuves génériques sur maquettes standardisées représentatives d'objets réels.

Il est à noter que ces essais ne se substituent en aucun cas aux essais sur munition et, s'ils tiennent compte de l'environnement réel des substances explosives, ne prétendent qu'en donner une réactivité relative et comparative.

Les maquettes utilisées sont :

* pour les explosifs
  - maquette acier (épaisseur 10 mm) contenant 5 kg de produit
  - maquette aluminium (épaisseur 1 mm) contenant 5 kg de produit
  - maquette acier (épaisseur 15 mm) contenant 50 kg de produit.

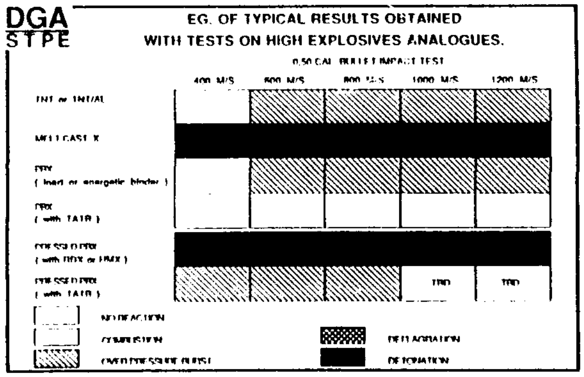
* pour les propergols
  - maquette acier (Ø 120 mm) avec chargement à canal central contenant 5 kg de produit
  (On peut noter la création prochaine d'une maquette de diamètre extérieur plus élevé pour tenir compte du problème de l'effet canal (4))

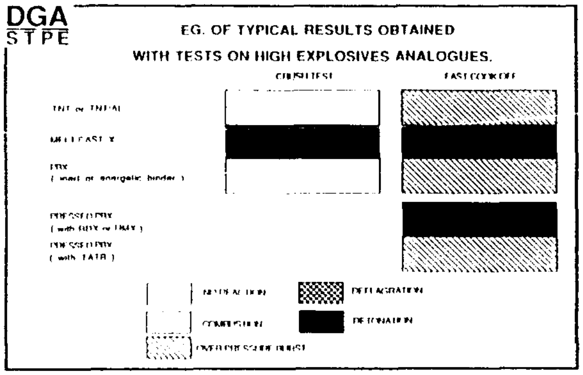
* pour les poudres pour armes
  - douille acier Ø 90 mm contenant 2 kg de produit
  - douille combustible Ø 90 mm contenant 2 kg de produit

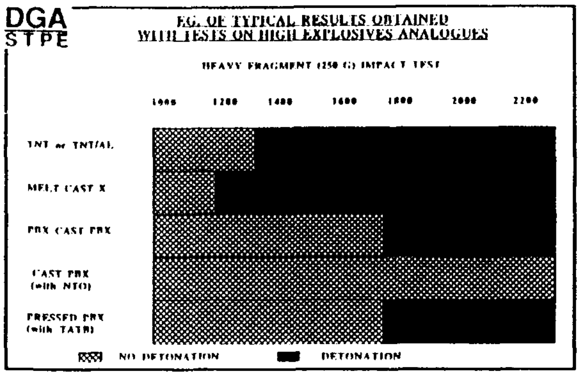
et les principales agressions étudiées :

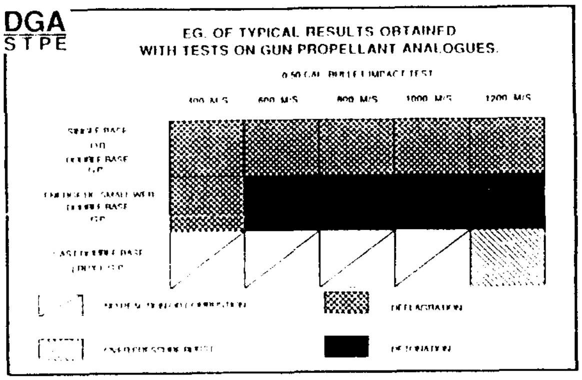
* impact de balle cal 12,7 (vitesses variant de 400 à 1200m/s)
* impact de fragment lourd (bille de 250 g - vitesse jusqu'à 2400 m/s)
* écrasement sous faible vitesse par un boulet de 8 kg
* impact de jet de charge creuse Ø 62 mm (avec atténuateur acier d'épaisseur variable 10 à 360 mm)
* incendie de kerosène (bac de 2 m x 2 m)
* échauffement lent (3,3°C/h)

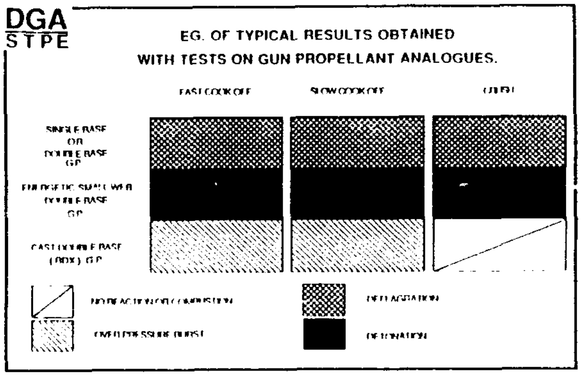
Exemples de résultats





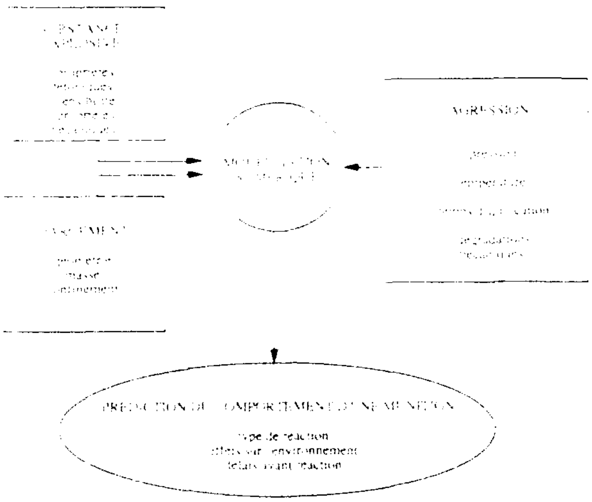






5 PREDICTION DU COMPORTEMENT

Un certain nombre de modélisations numériques sont en étude pour prédire, à partir des caractéristiques fondamentales d'une substance explosive (données de sensibilité mais également propriétés chimiques, détoniques et mécaniques) et de la géométrie de la munition dans laquelle elle entre (confinement, diamètre...) le comportement de cette munition soumise à une agression spécifique, elle-même modélisée.



De telles modélisations ont en cours en France (principalement réalisées par DRET, DCN et SNPE) sur

- les impacts de balles
- les échauffements
- les impacts d'éclats
- les jets de charge creuse.

Si les résultats sont satisfaisants pour les phénomènes de transition choc/détonation (prédiction du type de réaction) ou d'échauffements (prédiction des délais avant réaction), les prédictions sont beaucoup plus difficiles pour les phénomènes de type transition déflagration/détonation ou transition retardée choc/détonation.

6 - LA PRISE EN COMPTE DES SOLUTIONS "SYSTEME"

La réactivité d'une munition soumise à une agression dépend non seulement de la nature de la substance explosive mais aussi de la masse, de la géométrie et de l'enveloppe du chargement. Il est donc possible de jouer sur ces différents facteurs pour réduire les risques potentiels et les réactions obtenues.

A titre d'exemples, citons :

- le scénario dit d'effet canal sur les propulseurs soumis à impacts de balle et pour lesquels les risques sont dus à la géométrie du chargement (rapport entre le diamètre du chargement et celui du canal central) favorisant les focalisations d'ondes de choc (4).
Ce problème est soluble par modification de ce rapport de diamètres, à prendre en compte dès la conception du propulseur.

- le problème de détonation par influence de deux charges explosives résolu par l'utilisation des chargements bicompositions, une composition peu sensible aux chocs entourant une composition centrale plus énergétique qui permettra de conserver le niveau de performances requis (5).

- les résultats obtenus en douilles combustibles qui ont montré qu'une même poudre qui réagit en déflagration lorsque soumise, en douille métallique, à un impact d'une balle de 12,7 (les vitesse variant de 385 à 1150 m/s), ne réagit plus lorsque chargée en douille combustible.

Ces solutions "système" peuvent également constituer une réponse au problème des performances. En effet, le simple remplacement, dans une munition, d'une substance explosive par une substance peu sensible peut entraîner une baisse d'efficacité inacceptable de cette munition, parce qu'une substance peu sensible est souvent moins performante mais surtout parce que son fonctionnement est différent. C'est alors toute l'archtecture de la munition qui est à reprendre : système d'allumage, géométrie, couplage avec l'enveloppe...

7 - CONFIRMATION A ECHELLE 1

Malgré le crédit porté par l'utilisateur potentiel de la munition aux travaux d'évaluation et de prédiction du comportement, la qualification d'une munition risque en pratique de n'être prononcée qu'après confirmation sur objet réel. En particulier, il semble qu'une démonstration à l'échelle 1 de la non détonation par influence d'une munition en configuration de stockage soit obligatoire.

De tels essais étant coûteux, ils devront généralement être réalisés en "sévérité accrue", par maximisation de l'agression.

CONCLUSION

MURAT : un label à la carte

Très attentive aux orientations prises tant par les pays de l'OTAN (particulièrement par les Etats-Unis) que par les instances internationales (ONU) en matière de label de munition à risques atténués (LOVA, IM, objets 1.6 ...), la France a jusqu'à maintenant préféré adapter ses critères d'acceptation au cas par cas, système d'arme par système d'arme.

A une liste d'épreuves obligatoires minimale, le maître d'oeuvre étatique de la munition ajoutera des critères d'acceptation spécifique en fonction de son application.

Il est important de souligner qu'au niveau des compositions (propergols, explosifs) utilisées, il n'existera sans doute pas de "formulation miracle" mais que le choix d'une composition pour une munition donnée dépendra de l'architecture de cette munition ainsi que de ses conditions d'emploi (mission, mais aussi conditions de stockage, transport...) et surtout des spécifications de performances vulnérabilité coût retenues par le maître d'oeuvre.

La munition idéale ne sera en définitive que le compromis optimal entre performances et faible vulnérabilité.

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Discussion

QUESTION BY MAXEY, UK: In the evaluations, many pressure burst responses were noted. In France, is this an acceptable response and what parameters (eg pressure level, fragment throw) defines a pressure burst?

ANSWER: The experiments (tests) presented are the evaluation tests and non-acceptance tests associated with the precise criterion. The dummy utilized in these tests include safety plugs. At the time of a "over pressure burst" reaction type the plug is ejected but the rest of the dummy is intact. The question is in the case of a reaction of type 4 or 5 according to the definition of NATO (non-violent) and then by no means comparable to a deflagration.

QUESTION BY HELD, FRG: Should not the PASS/FAIL criteria correlate with munitions - quantity, confinement, configuration - and not on substances alone?

ANSWER: The tests in full-scale are costly and carried out in limited quantity (for example, people only carry out bullet impact tests of a certain caliber, at a certain velocity, etc.). The test of interest on a substance is allowed to extend the results obtained on similar aggression (for example on the behavior of a model generated for bullet impacts). That level of acceptance criterion enable us to look at same substances, by transportation and storage the ONU and NATO AC 258 required, by class object 1.6, such criterion associated with test series 7 ONU.

The United States Air Force Explosives Hazards Reduction Program

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SUMMARY AND INTRODUCTION

United States Air Force military operations require large amounts of conventional high-explosive munitions. These materials must be stored in accordance with Air Force, NATO, and host country regulations, and in large part consist of hazard class 1.1 mass-detonating munitions. Because of limited real estate available in many theaters and the current quantity-distance (Q/D) requirements for safe storage, significant portions of the available munitions inventory are either stored under waivers or are malpositioned (i.e., stored in locations remote to the airbases).

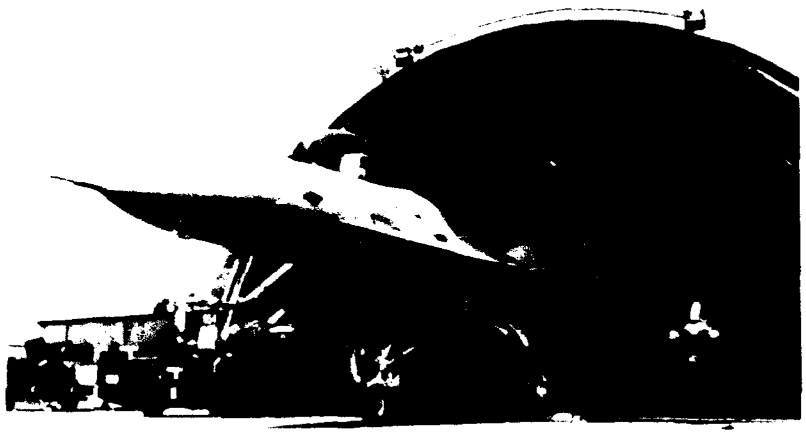

Figure 1. F-16 in Hardened Aircraft Shelter

The major objective of the United States Air Force Explosives Hazards Reduction (EHR) Program is to gain full combat capability by allowing required munitions to be safely stored at the base of intended use. Reduction of munitions hazards will significantly reduce air base vulnerability as accidents or attacks on munitions stocks will not result in catastrophic collateral damage. The long range goal of the Air Force EHR program is to complete transition to insensitive or less sensitive munitions in all major weapon systems as soon as is practical without significant loss of weapon performance or reduction in operational effectiveness. The EHR Program encompasses more than the development of insensitive High Explosives and Desensitized High Explosives to provide chemical solutions to reduce munitions hazards. The immediate goal of the United States Air Force is to reduce the hazards presented to inventory munitions by developing and incorporating energy suppression devices such as barriers, shields and diverters, redesigning munitions packaging, and applying innovative storage and handling techniques. These activities will permit the reduction of safety imposed restrictions (Q/D limitations) associated with these munitions. This paper presents the progress being made in attaining the Air Force immediate goal including key initiatives, ongoing and planned.

BACKGROUND

No matter how fast, sophisticated or versatile the fighter or bomber may be, without munitions it is ineffective.

Without munitions war is difficult and ineffective. Munitions support the full spectrum of conflict. Bullets, grenades and rocket launchers permit ground defense to provide security from ground attack. Air defense missiles and anti-aircraft guns provide security from air attack. Bombs, missiles, and bullets used to carry war to the enemy are the tools with which the war is won.

Historically, explosives and propellants have posed a major challenge to military users. The transportation and storage of large amounts of munitions are necessary to modern warfare, but present significant hazards to friendly forces because of the possibility of inadvertent explosion and mass destruction of the munitions and surroundings. Large quantities of munitions are needed to conduct war. Additionally, storage space is needed for bomb components: fuzes, boosters, fins, etc. While these are relatively low in explosive weight, storage volume required for these items is significant.

Large land areas are needed to accommodate the safety clear zones for explosives. This land, particularly in Europe, is expensive and sometimes not available at any price. The amount of explosives for each storage facility must, therefore, be tailored to fit the land available. Storage facilities which can physically contain 500,000 pounds of explosives are limited (on the average) to around 60,000 pounds because of land constraints. This limitation has resulted in the situation where munitions in the quantities required are not at the bases where they are needed. These munitions may be stored at another base or at major Air Force central storage areas.

Since these munitions are not where they are needed, they must be transported, sometimes over great distances, to the base of intended use. Shipments may be made by sea transport or we may have to rely on host nation civilian transportation resources which are to be nationalized at the outbreak of hostilities. Central storage areas are extremely vulnerable to enemy action. The bulk of the stocks are stored in open revetments and not in munitions storage igloos. Destruction of these stocks or interdiction of supply lines to the bases needing these munitions is likely. A number of mechanisms or stimuli can initiate an explosion of a single round of ammunition, and the inevitable result has been the propagation of sympathetic detonation throughout the munitions storage site, with a total loss of the munitions and, more importantly, personnel and materiel in the local area. Because of the violence of the reaction to various stimuli, large safety zones are required around munitions, The size of these safety zones increases as the number of munitions which are likely to react simultaneously increases. The term Maximum Credible Event (MCE) is used to quantify the largest simultaneous explosive reaction possible (in terms of pounds of TNT equivalent) in any given situation. For example, the MCE for a single MK82 bomb is 192 pounds. The MCE of a stack of 312 MK82 bombs is 59,904 pounds. The MCE can be controlled to some extent by the way munitions are stored, packaged and constructed.

The goal of the Air Force Explosives Hazard Reduction Program is to reduce MCE

GOAL

In order to establish a program to reduce munitions hazards, in September 1987 a Memorandum of Agreement (MOA) on a Joint Requirement for Insensitive Munitions (IM) was signed by representatives of the US Army, Navy and Air Force. This MOA established a joint service insensitive munitions policy for reducing the threat (to survivability of US ships, aircraft, weapons carriers, tanks, other weapons platforms, and stockpiles) posed by munitions and their reactions to unplanned stimuli. This policy extends beyond the development of insensitive chemical materials [Insensitive/Desensitized High Explosives (IHE)/DHE)] as the solution to the problem and includes the use of improved mechanical/electrical design concepts to reduce munitions hazards. Each Service was tasked by the MOA to implement a system for planning, funding, and executing its IM efforts.

EHR PROGRAM BENEFITS (PAYOFF)

- ***Reduced environmental impact and reduced need for waivers and exemptions to explosives safety criteria.***
- ***Improved air base survivability and combat sustainability through more effective storage of munitions.***
- ***Improved efficiency of munitions storage by providing worldwide on-scene & on-call EHR and facility site planning assistance.***
- ***Improved explosives facility site planning capability by providing guidance in the form of handbooks and on-site training.***

As defined in the USAF's EHR Master Plan, the immediate goal is to reduce the hazards presented to inventory munitions by developing and incorporating energy suppression devices such as barriers and diverters, redesigning munitions packaging, and applying innovative storage and handling techniques. These activities will permit the reduction of safety imposed restrictions (QD limitations) associated with these munitions. The long-range goal of the program is to complete transition to insensitive or less sensitive munitions in all major weapon systems as soon as practical without significant reduction in operational effectiveness. IM requirements will be included in all new munition programs through MIL Standards, Specifications, and Program Management Directives (PMD). To the extent practical, all munitions shall be made to meet the IM criteria (MIL STD 2105 "Hazard Assessment Tests for Non-Nuclear Ordnance"). Practical constraints include, but are not limited to, technical feasibility, affordability, inventory, shelf life, and return on investment. If a munition cannot be designed to be insensitive, it will be made less sensitive by incorporation of appropriate and feasible IM design features. Munitions that are not made insensitive will be examined periodically to determine if emerging technology or other factors can make the munitions less sensitive.

The Air Force IM policy directives require that all US munitions will be designed to minimize the effects of unplanned stimuli. While the standards for such occurrences could be satisfied by insensitive energetic materials, these materials are presently not available and it would not be feasible to replace the explosives in all inventory munitions. Therefore, the long range policy, to transition all major weapon systems to insensitive or less sensitive munitions, must await development of a chemical solution which is several, if not many, years away.

KEY INITIATIVES

Several key initiatives of the IM Program are listed in table 1.

Table 1. Key Initiatives

1. **Buffered storage** prevents propagation between stacks of bombs in storage. Tests have proven that barrier materials placed between stacks of bombs can prevent explosive propagation. The concept has been approved by the Department of Defense Explosives Safety Board (DDESB). Barrier materials which have been approved include 20mm ammunition and certain CBUs. Since these are not universally available, a generic buffer program using earth, sand, gravel, and manufactured barrier materials has been initiated. The generic buffered storage program will allow increased munitions storage in the same land area and limit the effect of enemy attack and terrorist actions on a munitions storage area.

2. **Barriers/shields and packaging** designed to prevent the propagation of one munitions item to the next will reduce the MCE. Barriers can be placed inside or outside munitions containers or between bombs on parked aircraft. Simple changes to the way munitions are packaged, such as orienting missiles within a container so that the warheads do not align, can also reduce the MCE. Effective barriers can limit the maximum credible event to one munitions item in a magazine full of munitions or one bomb on an aircraft. Barrier and packaging technologies will result in significant reductions in Q-D required. It will also reduce the effect of enemy or terrorist attack. The use of barriers has already proven successful with 40mm grenades, and propagation between two MK-84 bombs on the wing of an F-16 has been prevented. Other munitions being addressed for barrier technology are the MK-20 Rockeye, CBU-87, and CBU-89. All munitions could benefit from this technology.

3. **Flight line storage bins** will reduce many of the hazards associated with explosives operations on the flightline. Proof of concept testing for a flight line storage bin has been completed. A significant increase in sortie generation is possible.

4. **Hardened aircraft shelters (HAS)** provide an opportunity to increase sortie generation. When an aircraft load of munitions detonates within a HAS, massive fragments are projected and large safety distances are required around the HAS. Scale model tests have shown that if the MCE could be reduced to 1000 pounds or less, no significant fragment hazard would exist outside the HAS. Barrier technology could limit the MCE of a loaded aircraft to 1000 pounds or less and reduce or eliminate the Q-D requirement around HAS.

5. **Munitions site surveys** will be conducted to determine how both existing criteria and IM initiatives can be best applied at the air base. EHR initiatives needed to resolve specific problems can also be identified. This evaluation will include a site plan and storage planning documents. In addition, the site survey team will provide munitions site survey training to those commands desiring this type of service.

6. **Munitions Storage Modules (MSM)** are less expensive alternatives to concrete/steel arch igloos. Large Scale testing on MSM was conducted in 1989. Engineering design changes resulting from the testing are being completed. Small scale tests, to verify these changes, and the final design drawings need to be completed before MSM can be certified by the DDESB. MSM will provide the same protection as a concrete arch igloo, at less cost. MSM can be used cost effectively to provide covered, deep, secure storage for munitions at central depots.

7. **Lightning protection** is a key initiative for munitions storage. Lightning protection is now required by DDESB for all munitions storage facilities, and appears to be a default requirement. However, the Air Force has never provided lightning protection for open storage of munitions and there is no evidence of any accidents resulting from lightning-caused detonation of these munitions. There is good technical evidence that properly stored munitions do not need lightning protection. Providing this protection for open storage of munitions in Europe alone would cost at least 10 million dollars. A study and, if necessary, testing will be conducted to determine if the requirement for lightning protection of open storage munitions is valid.

Each of the above key initiatives will be discussed in greater detail in the following paragraphs.

BUFFERED STORAGE

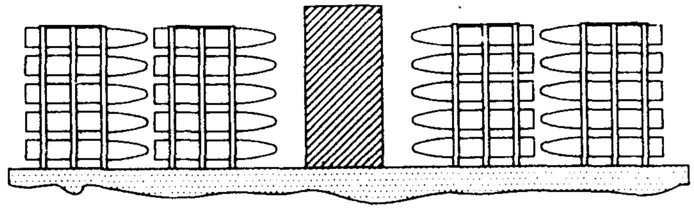

Figure 2. Buffer Materials can prevent propagation between stacks of munitions

Previous Air Force Testing Programs have shown that propagation between stacks of bombs could be prevented by using air and or munitions items as buffer materials between stacks of MK-82 and MK-84 bombs in munitions storage igloos[1]. Various densities of buffer materials were placed between two stacks of bombs in an attempt to prevent propagation from one stack to the other (see figure 2). Each stack contained about 60,000 pounds net explosives weight (NEW). The munitions buffers selected were of sufficient densities to defeat fragment attack. Areal densities of 500 pounds per square foot were successfully tested. Separation distance was found to be important because of overpressure in an enclosed space. An acceptable separation distance proved to be 38 feet between bomb stack boundaries. While it is convenient to use munitions as buffers, the munitions items tested as buffers are not always available. Since only tested items may be used as buffers, it is imperative that other readily available materials be qualified for use.

Several factors must be considered in designing these buffering systems as shown in table 2. These include cost and availability of the raw materials or final products, the ability to handle buffer materials with existing equipment and the labor needed to maintain, emplace and remove the buffer materials as well as the performance of the buffer system.

Table 2. Buffer Material Considerations

COST AND AVAILABILITY: Since large amounts of buffer materials will be required, it is necessary to minimize the cost for these systems. If they can be fabricated from local, readily available materials, significant savings in shipping costs could be achieved.

HANDLING COMPATIBILITY: The final buffer must be compatible with existing handling equipment. Weight and size limitations will be dictated by the capacities of available forklift trucks, door sizes of igloos and magazines, and other logistics considerations of this nature.

LABOR REQUIRED: The labor required to emplace, maintain and remove these buffer materials is a key factor. Materials which need little or no continuing maintenance, such as concrete blocks, are preferred over more labor intensive systems.

BUFFER PERFORMANCE: The buffer must be able to sufficiently mitigate the fragment attack from the detonation of a 60,000 pound NEW stack of bombs to prevent propagation to the next stack of bombs.

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[1] *This concept was approved by the Department of Defense Explosives Safety Board (DDESB). At the 299th DDESB meeting, the following subparagraph h was added to DOD 6066.9-STD Chapter 9 paragraph b.1: "If DDESB approved buffered configurations are provided, the NEW for Q/D purposes is the explosive weight of the largest stack plus the explosives weight of the buffer material."*

BARRIERS AND PACKAGING

Currently fielded munitions containers are designed to meet requirements defined in MIL-STD 648A "Design Criteria for Specialized Shipping Containers" and XWS-32350 "Critical Item Development Specification for Containers". These documents address specifications for vibration, environment, handling, maintainability, size and weight. The following stimuli which are not currently addressed in container design are of immediate and critical concern to the Air Force: cookoff (fire hazard), bullet impact, fragment impact and sympathetic detonation. With the application of modern armor technology and advanced materials, a munitions container can be designed to protect the weapons from unplanned stimuli; but, should a reaction occur, sympathetic detonation from container to container will be mitigated. This class of physical mitigation or suppression devices is being investigated to improve safety and to permit reduced MCE and Q/D.

Figure 3. Barriers can prevent propagation between munitions

Barriers, diverters and packaging with internal or external shielding provide a low cost opportunity to reduce munitions hazards. It is the intent of the Air Force to continue to develop and implement a comprehensive barrier technology effort. The Air Force has been conducting a technology investigation of a deformable mechanical diverter which separates MK-84 general purpose bombs (see figure 3.). This barrier typically runs the length of the weapon and varies from 6 to 12 inches in width and 2 to 4 inches in thickness, depending on the material used. The combination of physical separation with a shock reduction media is intended to reduce the peak shock experienced by the adjacent weapons to a level below the initiation threshold for the explosive used. The diverter also acts as a deflector for the bulk of the weapon fragments so that either they do not strike the adjacent weapons or their impact angles are very low. The effectiveness of this technique has been demonstrated in a configuration of four MK-82 bombs in a row, two bombs high, facing a similar configuration nose to nose. Tests also included bombs configured with fuzes and fins. In one case, 15 of 16 bombs in the test were not sympathetically detonated by the donor. Many MK-82 tests were conducted; some resulted in successes, others failed. Diverter technology efforts to date strongly indicate that diverters can deter sympathetic detonation. The reasons for diverter failures encountered with MK-82 bombs are being investigated.

Diverters will deter sympathetic detonation in many situations, but it is necessary to acquire a thorough understanding of the detonation products (fragments and blast characteristics, etc.) and how these products affect adjacent rounds. Only then can we select materials and design a diverter that will reliably deter sympathetic detonation. One of the major objectives of this task is to define and verify modeling and testing techniques to assist in developing and implementing diverter/barrier technology.

The Air Force has an operational requirement to store 40 MM High Explosive Dual Purpose (HEDP) rifle grenades in Security Police armories. These items are Hazard Classification 1, Division 1 (C/D 1.1) because they mass detonate and they can be stored only in the munitions storage area.

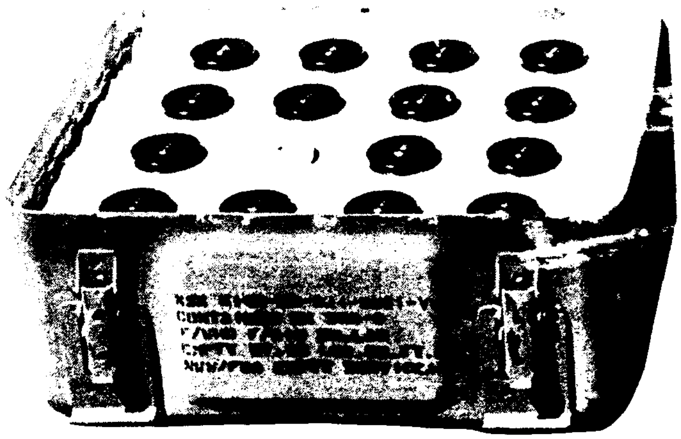

Figure 4. Prototype container for 40MM (M433) grenades

The Air Force has conducted a series of tests using a new packaging configuration for the HEDP rounds (see figure 4.), and has shown that, the maximum credible event (MCE) can be limited to one round. Also, testing has shown that, when the containers are stacked, initiation of the shaped charge in the upper container does not propagate to a round directly below in the lower container. This means the grenades can be reclassified to CD 1.2 non-mass detonating, and can be stored in the armories where they are needed.

Cluster Bomb Units (CBU's) in the current inventory are being replaced by the CBU-87 (Combined Effects Munitions) and CBU-89 (Gator Antitank and Antipersonnel Mines). The inventory CBUs are assigned C/D 1.2. However, the new CBU-87s and CBU-89s are assigned C/D 1.1. and require large Q/Ds because they mass detonate. Storage capacity for C/D 1.1 munitions is already limited. The introduction of CBU-87 and CBU-89 creates additional storage problems, which can be avoided if modifications can be made to the munitions or munitions containers which allow them to be classified as C/D 1.2. The CBU-87s and CBU-89s are packaged two in a CNU-327E container (see figure 5.). It may be possible to stop propagation by modifying the packing material within the container or by placing external mitigating material shields on the outside of the container. To this end, testing will be done to better understand close-in effects of the detonation of a CBU-87 and CBU-89. Characteristics of the individual submunitions are known; however, detonation of an intact CBU-87 and CBU-89 has not been characterized. This characterization will be conducted both on single items and on a standard storage configuration (CNU-327E containing two CBU's). Information derived from the munitions characterization test, coupled with known characteristics of candidate barrier materials and the sensitivity of the submunitions, will determine if redesign is feasible. External modifications to the CNU-327E may be required to ensure sufficient mitigation of fragment, blast, and shaped-charge effects.

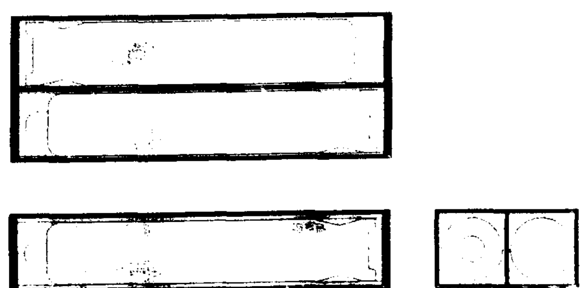

Figure 5. CBU Container with Barriers

Modeling and validation of the modification/redesign is accomplished in four stages. Small-scale tests using sections of the proposed container determine if the design is feasible and obtain relative measures of the mitigation/protection afforded to the submunitions. Single-package tests determine if propagation can be prevented between two CBU's in the same container (these tests may be omitted if munitions characterization tests indicate there is little likelihood that propagation between individual items can be prevented). Unconfined container-to-container tests determine if propagation can be prevented vertically, horizontally, and front to rear. If the foregoing tests are successful, a standard hazard classification test series is accomplished in accordance with Air Force Technical Order 11A-1-47.

FLIGHT LINE STORAGE BINS

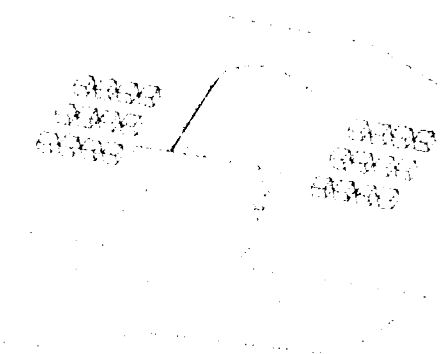

Figure 6. Bins, each containing one sortie of munitions, can be located adjacent to aircraft operating areas. Other munitions can be dispersed in bins throughout the airbase.

Mission requirements and physical constraints have created a requirement for waivers and exemptions to explosives safety criteria at many Air Force Bases. These waivers and exemptions identify hazardous conditions which threaten both U.S. and other nations assets and personnel. Aggressive action must be taken to eliminate the hazard or protect the personnel and assets affected. Funds to construct new facilities and/or purchase additional land are not available. One relatively inexpensive solution to many of the conditions requiring waivers and exemptions is the use of munitions storage bins or in-ground munitions containers (see figure 6). In addition to reducing required clear zones, munitions storage bins will provide for improved survivability and sustainability at both permanent and bare base facilities.

The objectives of the bins are to:

1. Reduce environmental impacts, explosives safety separation distances, waivers and exemptions to explosives safety criteria, and threat to personnel, munitions, facilities, and other assets;

2. Increase survivability and sustainability of combat operations by safely prepositioning several days of munitions stocks at aircraft operations areas; and

3. Provide alternative munitions storage methods to support combat air operations and increase the survivability of munitions stocks.

HARDENED AIRCRAFT SHELTERS

Barrier and flightline storage bins or in-ground munitions containers have the potential for solving the most serious operational limitation problems facing our logisticians. For example, hardened aircraft shelters (HAS)

are generally sited for the maximum quantities of munitions they are permitted to store (only 10,000 pounds net explosives weight). This limits the amount of explosives to accommodate multiple sortie generation. The explosives safety clear zone required to store 10,000 pounds of explosives in a hardened aircraft shelter is 1,335 feet. If the munitions are stored on the ground outside of the shelter the required distance is 1,250 feet. If munitions storage bins were used to store the additional sorties required at the aircraft shelter, the shelter could be sited for 4,000 pounds NEW (enough for one sortie) and the required safety distance could be reduced to 985 feet. Proof of concept testing indicates that the inhabited building distance required around munitions storage bins would be 760 feet. The munitions storage bins could be located within the 985 foot clear zone of the HAS and therefore effectively reduce the clear zone around hardened aircraft shelters from 1335 feet to 985 feet. Bins/below-ground storage containers make it possible to store a significant number of munitions, increase sortie generation and not exceed Q-D for 4000 pounds NEW.

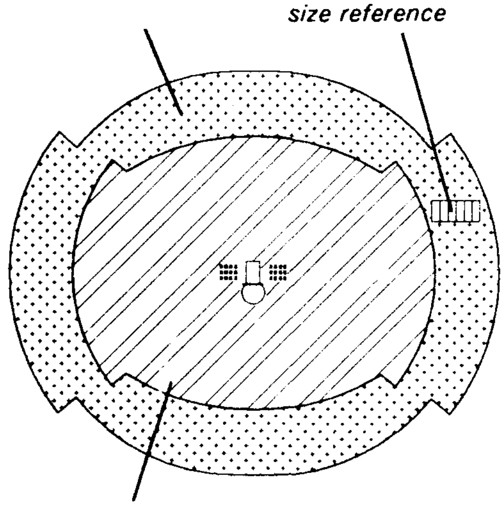

Figure 7. Expected Clear Zone Reduction

Munitions SITE SURVEYS

Airbase munitions site surveys and munitions hazard reduction planning will identify problems created by the presence of munitions, and quantify the scope and severity of the problem as it relates to airbase survivability and operability. These data will be used to quantify benefits gained by application of IM technologies and will help prioritize and justify funding for IM initiatives. These surveys will identify actual operational combat limitations and other restrictions limiting the unit's ability to effectively complete its combat mission. Surveys will address peacetime operational needs, pre-hostility build-up, and sustained combat operations. The surveys will particularly address explosives safety waivers and exemptions to determine what actions can be taken to reduce or eliminate them without degrading the mission capability. Surveys will consist of five phases shown in table 3.

Table 3. Five Phase Program for Munitions Site Surveys

Phase 1:

Determine munitions requirements. Review applicable documents to determine the total munitions requirements.

Identify explosives capacities for all storage, maintenance, assembly, holding areas, emergency munitions storage sites, hardened aircraft shelters and other areas that are identified as explosives locations.

- Identify USAF/MAJCOM, as well as funded and unfunded MCP/NATO munitions storage/operating facilities.
- Determine applicable national and international explosives safety/survivability criteria.
- Review existing approved explosives site plans and Host Nation approval documents if applicable.
- Obtain waiver, deviation, and exemptions documents if applicable.
- Determine the total explosives capacities and operational limits for all explosives locations (currently approved).

Determine the difference between existing storage capability and requirements.

Evaluate previously directed (pre-direct) munitions shipment for quantity and timing of munitions shipments.

- Review existing munitions pre-direct transportation plans for currency with relevant agencies.
- Validate pre-direct emergency munitions storage locations and storage capabilities.

Evaluate munitions assembly and delivery capabilities.

- Determine munitions personnel/equipment requirements & availability to sustain daily combat operations.
- Determine munitions personnel/equipment requirements & availability to receive pre-direct munitions shipments.

Phase 2:

Quantify survivability, sustainability, operability problems under existing operating conditions.

- Determine munitions shortfalls/overages and operational restrictions caused by munitions.
- Determine impact of pre-directed munitions receipt on combat operations.
- Determine the hazard posed by U.S. munitions on survivability, operability, and sustainability of the airbase.
- Develop a base map depicting munitions hazards affecting survivability/operability.
- Prepare documents describing operability and sustainability problems created by munitions shipments/operations.

Phase 3:

Determine enhancements possible to survivability, sustainability, and operability, through improved application of current safety criteria, re-warehousing munitions, or adding low cost enhancements such as barricades.

- Review existing waivers/deviations to determine if they are required/valid.
- Develop munitions storage plans for all munitions storage facilities, holding areas, other operating locations, and hardened aircraft shelters, if applicable.
- Prepare a revised explosives site plan indicating peacetime and wartime munitions, if applicable.

Phase 4

Quantify survivability, operability, and sustainability gains from application of current or ongoing IM initiatives.

- Develop munitions storage plans which depict storage gains through application of IM technologies.
- Develop explosives site plans to quantify gains in base storage capacities.
- Develop a base map to compare explosives hazards using EHR technologies versus current technologies.
- Document survivability, operability,and sustainability gains made through use of these technologies.

Phase 5:

Identify and quantify new initiatives/technologies which should be included in the Air Force EHR program.

MUNITIONS STORAGE MODULE

Standard munitions storage igloos are designed and certified to store a Net Explosive Weight (NEW) of 500,000 pounds. These igloos cost approximately $450,000 each. Tests conducted under the Air Force Munitions Hazards Reduction Program using a modular igloo have demonstrated the feasibility of this new design approach (see figure 8.), which would cost about $250,000 each. The igloo concept is based upon the integral connection of single precast concrete panels. Steel beams are cast internally in the panels and are assembled to provide most of the structural integrity.

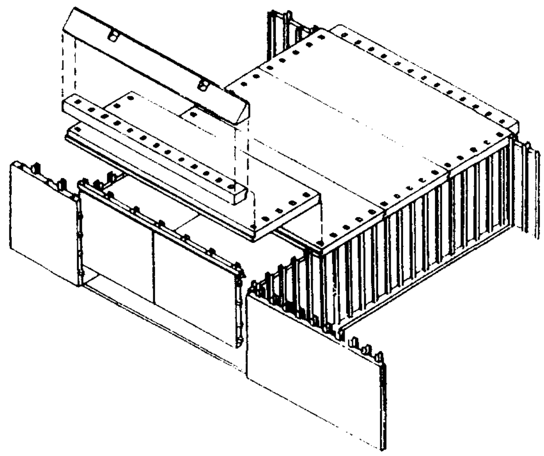

Figure 8. Munitions Storage Module

The MSM provides an increased explosive siting capability, more effective use of land and a substantial cost savings over standard steel arch and Stradley explosives storage facilities.

The general procedure for erecting the modular igloo is outlined in table 4:

Table 4. MSM Erection Procedure

Prepare the construction site and foundation

Place the precast floor slabs

Erect and hold in place the back wall and first section of each side wall (wall sections are joined to the floor slab by inserting the steel members into existing slots in the floor slab)

Place the first section of the roof (this stabilizes the first wall sections)

Continue wall erection and roof placement of each section until the basic structure is complete (wall and roof sections are attached to previously erected sections by slip joints)

Place door frame and doors

Place frontal retaining cap and wing walls

Cover the structure with soil overburden

LIGHTNING PROTECTION

Currently the DOD requires lightning protection for open munitions storage pads. The Air Force has not implemented that requirement and is being pressured by the Department of Defense Explosives Safety Board (DDESB) to do so. This is in spite of an apparent lack of information on the effects of lightning strikes on munitions. In fact, it appears that there have been no Air Force incidents of munitions exploding because of lightning strikes. In addition, the Air Force is unaware of any instances in service or industry where the main charge explosive inside unfuzed, cased munitions has exploded as a result of lightning strikes. Because lightning protection for open storage will cost \$10-20 M in USAFE, the EHR program office discussed the lightning hazards with Los Alamos, Sandia National Laboratories Albuquerque, and the U.S. Army Missile Command (MICOM), the latter two having lightning simulation facilities. These discussions indicate that the explosives inside unfuzed, cased munitions should not react upon attack by generic lightning strikes. This initiative will validate or try to eliminate explosive safety requirements for lightning protection.

CONCLUSIONS

The Air Force Insensitive Munitions/Explosives Hazard Reduction Program is a significant undertaking that has the cooperation and support of the major commands. The program serves the changing needs of the Air Force. It will facilitate base reductions and future operational requirements. Cost savings realized by implementing EHR initiatives will more than return the cost of this program. Improved safety and survivability of munitions stocks will provide significant operational benefits. This program has been fully included in Air Base Operability considerations to improve air base operations, survivability, and sustainability. The Air Force EHR program has several key initiatives which directly address the changing needs of the Air Force.

Key initiatives are in the barriers and packaging area. Barriers and packaging which can be designed to prevent the propagation of one munitions item to the next will reduce the MCE. Barriers can be placed inside or outside munitions containers or between bombs on parked aircraft. Simple changes to the way munitions are packaged, such as orienting missiles within a container so that warheads do not align, may also reduce the MCE. Effective barriers and packaging can limit the MCE to one munitions item in a magazine full of munitions or one bomb in a mission ready aircraft. This will also result in significant reductions in quantity-distances required, and allow more munitions to be stored in closer proximity to airbases, flightlines and hardened aircraft shelters (HAS) where they are needed.

Because munitions are critical to the war fighting effort, the hazards to friendly forces must be accepted but must also be minimized. The Air Force Explosives Hazard Reduction Program interfaces within the framework of the Air Base Operability mission to <u>defend</u>, <u>survive</u>, <u>recover</u>, <u>generate</u> and <u>support</u>.

Under the <u>defend</u> framework, explosives hazard reduction procedures will increase munitions storage capacity, and ensure that base defense ammunition and explosives can be stored at the base and locality of intended

use. Additionally, techniques which reduce hazards of munitions can enhance availability of munitions to the base defenders.

Survival can also be greatly enhanced by storage techniques, containers designed to mitigate propagation, and facilities which will lower MCEs and reduce both direct and collateral damage from enemy action.

To ensure survival of vital munitions resources, innovative storage facilities such as flight line munitions storage bins will disperse munitions stocks in the operating areas, provide protection from attack and reduce the need for large and vulnerable munitions storage areas.

The IM Program is recognized as critical to the survival of our tactical air forces, and will be pursued with vigor and a high priority sense of purpose.

With the advent of the Air Force IM program, reduced munitions hazards have become a design requirement for all munitions planned and in development. Improved defense and survival of munitions and user personnel make it much easier to recover from enemy attack, generate sorties and provide combat support to attack the enemy.

Discussion

QUESTION BY FRECHE, FRANCE: You have shown that reduction of risks can bring an important increase of quantities of munitions that can be stored in a given storage area. If you have insensitive munitions will you be able to increase again these quantities?

ANSWER: Yes! The ultimate solution to the Air force's storage problem is truly insensitive munitions using insensitive high explosives (IHE). When IHE is available, there will be no problems with storage. However, we believe that IHE will not be available for many years, and that expedient methods, such as buffered storage and underground bins next to hardened aircraft shelters are needed to improve storage problems in the interim.

QUESTION BY CHIZALLET, FRANCE?: The USAF has a strong interest with problems met in storage. This means an interest for NATO 1.6 risk division which mainly solves IM by just utilization of IHE to fill in the munition. This is not necessary with IM policy, where the only important point is result. What is the USAF position regarding this question?

ANSWER: It is our position that the insensitive munitions goal to achieve hazard classification/division 1.6 (C/D 1.6) will not be achieved in the near future. Maybe never! However, there are many ways to make munitions less sensitive, to reduce hazards to a more acceptable level and to thereby improve our storage problems and combat capability. We are actively pursuing methods to reduce munitions hazards to C/D 1.2 and C/D 1.4 using mechanical and physical means while awaiting the ultimate chemical solution.

ADVANCED GUN PROPULSION CONCEPTS AND INSENSITIVE MUNITIONS REQUIREMENTS: AN OVERVIEW OF US EFFORTS

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1. SUMMARY

This survey paper summarizes current US efforts in advanced gun propulsion technologies. The majority of these R&D efforts today focus on advanced solid propellants (including those specifically designed for low vulnerability characteristics), liquid propellant guns, electric guns concepts, and the ramjet cannon accelerator. While the motivation for these efforts is mainly improved ballistic performance, of almost equal concern are operational vulnerability as well as a hazards associated with the transportation, storage, and handling of munitions. A major concern for technologists today is how to reconcile these apparent contradictory goals. The goal of truly "insensitive" munitions is probably unrealistic. Less-sensitive munitions are, however, possible and desirable. It is now clear that operational survivability and vulnerability of gun-carrying weapon systems are affected to a significant degree not only by the sensitivity of munitions stored on-board, but also by the packaging, storage location, degree of confinement, compartmentation, and overall external and internal system protection. Munitions sensitivity or vulnerability can no longer be evaluated realistically in isolation from the weapon system. This has profound implications on insensitive munitions design and test methodology.

2. INTRODUCTION

Gun propulsion research and development efforts in the US are currently focused on improving the ballistic performance and achieving meaningful increases in overall system effectiveness. Reduction of weapon system vulnerability has become a major motivation during the last two decades with the growing realization that combat survivability is as important a factor in effectiveness as system lethality. With the additional backgound of catastrophic munitions fires on-board aircraft carriers, massive ammunition dump fires, and munition train disasters experienced in the last 25 years, it is not suprising that a consensus developed with a clearly stated goal to field only munitions (Ref 1) which are insensitive to the maximum extent possible.

Early studies showed that the elimination of sympathetic detonation could significantly increase survivability of ships carrying mixed stores of explosives and propellants, and that the use of less-sensitive gun propellants would dramatically reduce the number of M60 series tanks killed in battle

Insensitive Munitions (IM) Programs in the US Services have focused primarily on weapon platform survivability such as infantry fighting vehicles, tanks and ships, reduced vulnerability of rocket propellants and reduction of sympathetic detonation and response to cook-off of bombs in stores. Each service has different priorities. The Air Force is concerned with base magazine storage of munitions (survivability and quantity distance). The Navy concern is ship survivability. The Army's primary concern is combat vehicle survivability and munitions transport and storage safety.

Since the initial efforts began, a Navy-approved document, MIL-STD-2105A (Ref 2) has been developed which defines the mandatory tests and the pass/fail criteria for the assessment of safety and insensitive munitions characteristics of all non-nuclear weapon systems and munitions, munition systems, and explosive devices. Program managers are now responsible for planning and executing a hazard assessment test program which includes a test plan based on a realistic life cycle threat a hazard environmental profile.

In virtually all advanced gun propulsion programs the dominant ballistic goal is to achieve substantial increases in kinetic energy. The need for higher muzzle velocities may become clearer as the benefits and system burdens of very high velocities become better defined. However, it is becoming increasingly more difficult to extract more kinetic energy from a given conventional gun envelope. While conventional wisdom says that we are at the limit of muzzle velocities for chemical gun propulsion, velocities on the order of 3km/s have been demonstrated (Ref 3-4). However, the thermodynamic efficiency decreases at very high velocities to the point that such an approach is typically not attractive from a tactical systems perspective.

The options available to increase the kinetic energy of projectiles are: (1) combine modest incremental improvements in projectile design, gun pressure limits, propellant energy density, and progressivity; (2) develop a larger, longer gun; (3) explore alternative, non-conventional gun propulsion options for impr[illegible] ballistic performance at a system penalty less than the first two options.

The challenge to conventional munitions designers is now two-fold. In addition to the usual requirements of increased performance and effectiveness, the requirement for reduced vulnerability and increased survivability of the munition is also established by the IM policy. Increased energy and less sensitivity are not easily achievable in concert and novel approaches and trade-offs are required as described below. While advanced conventional gun propulsion

approaches are indeed making remarkable progress, the hope is that in the long term electric gun propulsion options will result in more effective gun systems than possible by conventional means.

3. US PERSPECTIVES ON INSENSITIVE MUNITIONS

Specific IM requirements and thus the assessment tests must be placed in the perspective of the specific weapon system in which munitions are to function. Weapon systems and threat environments differ greatly between the services. Guns systems on board ships, aircraft, tanks, armored personnel carriers, self-propelled artillery, towed artillery, etc. all face considerably different battlefield threats and may have different levels of acceptable survivability. These differences must be accounted for in establishing the IM criteria and assessment tests for munitions.

In this section we briefly summarize the US Army and Navy perspectives on Insensitive Munitions with respect to gun propulsion technologies. The views of the US Air Force reflect to a significant extent both Army and Navy views. While the focus here is gun propulsion, Boggs and Derr, (Ref 5) describe many of the same issues and problems for hazards of solid propellant rocket motors.

3.1. Navy Perspective

The US Navy has led the way towards establishing Insensitive Munitions requirements and test protocols largely as a consequence of the importance of ship survivability. To a significant extent the requirements and protocols served as models for the Joint Services Requirements Document. Any advanced naval gun systems will be required to meet Insensitive Munition requirements (Ref 1-2,6-9). To that end the USN is collaborating with the other Services on some advanced (non-solid) gun propulsion technologies (e.g., the electrothermal/chemical (ETC) gun system to meet the emerging anti-ship missile threat in close-in weapon system (CIWS) application). Because resources are limited, however, and because there remains a considerable inventory of solid propellant based gun weapon systems, there remains a continuing focus to meet the goals of IM requirements in these more conventional systems. While much of the early effort was based upon application of nitramine propellant technology, more recently there has been added emphasis on the ammunition as a total system. That is, improvements are sought for the total gun munition package in its entire logistics life cycle. An example is described below.

For fixed cartridges, substitution of PBX explosive in the warhead should be accomplished in concert with substitution of LOVA (low vulnerability ammunition) propellant in the propulsion system. Furthermore, at the subassembly level, consideration needs to be given all the components, as well. The relative roles of the propellant, the igniter design, the igniter material, the case design, and even the crimp force must be understood and addressed as a system. Similarly, packaging, stowage arrangement, fragment and/or fire protection systems need to be given proper attention not only in credible event analytical assessment, but also in specific end item testing.

Experience in developing an improved 76 mm cartridge serve to illustrate many of the above points. A LOVA propellant was developed (and qualified in accordance with Ref 5 to replace the single-base M6+2 propellant (Ref 10). This LOVA propellant featured many attributes sought in a propellant required to meet IM requirements (e.g., higher ignition temperature); yet until the BENITE igniter material was replaced with a special LOVA Igniter (LI) material and until the drawn steel cartridge case was replaced with a spiral-wrap case design, the cartridge was unable to meet the Navy's IM requirements. Regarding the igniter, in fast and/or slow cook-off the BENITE igniter material ignited at a temperature well below the LOVA propellant resulting in an igniter cook-off and subsequent aggressive response of the cartridge. Similarly, even when special temperature resistant LI materials were incorporated so that the LOVA propellant cooked-off before the igniter (in a localized zone), there was still an aggressive response of the cartridge until the drawn steel case design was replaced with a spiral-wrap case (capable of venting at low pressure).

Finally, despite demonstration of the improved cartridge to meet IM requirements, a simulated shipboard magazine test revealed that a characteristic of the fire protection system prevented realization of the full potential of the improved cartridges. In testing for conformance to IM requirements (Ref 9), it had been demonstrated that the response of cartridges improved, typically, from an aggressive propulsive deflagration to a mild burning response. In the mock magazine simulation test (including sprinkler protection system), it was learned that the IM test permissible burning response can still result in catastrophic response as cook-off propagation of adjacent munitions in a confined storage arrangement is likely. The simulated systems tests demonstrated that application of large quantities of water from the existing sprinkler system was effective in controlling cook-off propagation. However, the response characteristics of the sprinkler sensors/system needed to be improved to prevent cook-off propagation. In summary, then, consideration and complete understanding of the ammunition (and all its parts) in its entire logistics life cycle is vital to the success of the IM initiative.

3.2 Army Perspective

Rocchio, et al. (Ref 11) describe one of the earliest attempts in the US to find low vulnerability ammunition (LOVA) alternatives to conventional tank ammunition. Only recently did Insenitive Munitions Requirements (Ref 1) and the associated test protocols (Ref 2) become Army policy. While a standard test methodology is very important and useful, it has been found to be difficult to apply the Navy standard methodology to Army systems. MIL-STD-2105A specifies tests that are of marginal relevance to the environment in which Army munitions may be exposed. Another issue, however, is that passing all the required standard tests summarized below still does not necessarily result in munitions satisfactory for an Army threat/hazards environment.

There are three sets of tests used to assess or qualify energetic materials/munitions with respect to hazards. The sets of tests are (a) IM Tests (described in MIL-STD 2105A), (b) system vulnerability tests (developed to assess system survivability requirements and (c) the UN Hazard Classification Tests, described in Army TB 700-2, used for

shipping and storage purposes. Table 1 lists the seven standard IM tests.

Table 1. US Insensitive Munitions Test Summary

Test	Passing Criteria
Fast cookoff	burning permitted
Slow cookoff	burning permitted
Bullet impact	burning permitted
Fragment impact	burning permitted
Symp. detonation	no propagation of detonation
Jet impact	no detonation
Spall impact	no burning permitted

The latter two tests are only required if the threat hazard assessment determines that they are credible threats. The slow cookoff test is also waived for Army systems if no realistic scenario can be described. All tests are described in MIL-STD 2105A, which has recently been approved for Navy use and is available for use by the other services.

Hazard Classification tests are run in conformity with UN procedures and are described in Army Technical Bulletin TB 700-2. The tests are intended to assess the response of the ammunition in its shipping and storage configuration. As part of the Hazard Classification Process, all munitions are subjected to a sympathetic detonation test and a bonfire (fast cookoff) test, which are very similar (but not identical) to their IM counterparts. To qualify for Hazard Class 1.6 (Extremely Insensitive Detonating Substance), munitions must be subject to a slow cookoff test and a bullet impact test, which are also similar to, but not identical with, their IM counterparts.

The IM Tests do not necessarily address Army system vulnerability problems. For instance, it would be very unusual for an army munition to be hit by a 16 gram fragment at 8300 fps (the IM Fragment Test). Likewise, it would be very unusual for an Army munition to be exposed to a heat source which would result in a 6 degree F per hour heating rate (the IM Slow Cookoff Test). On the other hand, it is quite possible that a propulsion charge could pass the IM Shaped Charge Impact Test, but the burning reaction could be sufficiently rapid to destroy a tank ammunition compartment.

While this technical view is not an official Army position, efforts are underway to develop a unified, coherent policy tailored for Army systems.

The Army position is that if the munition does not pass the insensitive munition tests using the recommended procedures, a waiver must be granted to type classify the item. An essential element in approval of the waiver is an agreement between the developer and the user to correct the deficiency.

Recently, this policy was tested only partially for a kinetic energy tank round which contains the propellant JA2. The IM tests showed that the munition failed the fast cookoff, fragment impact and spall impact tests. After review of the alternatives it was determined that the technology was not readily available to correct all of these deficiencies and the research centers were directed to allocate resources to solve these problems. The exercise further substantiated the need to build flexibility into the test procedures and to make a distinction between logistic and tactical type tests.

The Army is currently reconciling these test methodologies in a coherent framework to be published as MIL-STD-2105B.

4.0 CURRENT MAJOR US GUN PROPULSION EFFORTS

In this section we survey many of the gun propulsion technologies currently under investigation in the USA. The discussions include brief technical descriptions, the underlying motivation for the efforts, a summary of the current technological status and technical challenges, and a brief review of the insensitive munitions aspects of these gun propulsion approaches.

4.1 Advanced Solid Propulsion

4.1.1 Energetic Materials

The energetic material is often the most critical component which determines vulnerability of munitions (Ref 11). There are, however, exceptions to this rule and thus the entire munition [projectile, case, ignition system, additive packages, propellant, storage system, etc.] must be treated as a system and the interplay of critical components identified. While the system aspects of vulnerability reduction of ammunition must be always be kept in mind, the discussion here will focus on solid gun propellants. The goal of US research has been "low vulnerability" ammunition (LOVA), not "no vulnerability" ammunition!

The mechanism of response of munitions to a threat stimulus must be understood in order to have a reasonable chance to develop improved energetic materials. The effective threat stimulus experienced by a propellant depends on: the initial threat, the armor or other protection that filters this threat, and the local stowage configuration of the rounds themselves. For armored systems there are two fundamental threats: fragment/spall impact and hypervelocity impact (HVI) with the latter resulting from either chemical energy jet (CE) or kinetic energy penetrator (KE) threats. Fire and heat are secondary threats as they arise from prior initiation of a munition by a primary threat.

Spall. The principal initiation mechanism associated with spall impact of gun propellants has been shown to be thermal ignition by conductive heat transfer from the spall. The detailed mechanism is very complex and is controlled by the chemical, mechanical, and thermophysical properties of the propellant, Figure 1 (Ref 12). Extensive research showed that this threat could be mitigated by propellants with high thermal ignition thresholds, characteristics which cannot be achieved with nitrocellulose-based formulations but are found in nitramine composite formulations.

The role of the thermal decomposition chemistry of the energetic solid and polymer matrix are reasonably well understood. The energetic solid should have a high temperature for onset of thermal decomposition. Nitrate esters are inferior to the nitramine and nitro groups in this respect.

For the polymer matrix, thermal decomposition should occur at temperatures at or slightly below that of the energetic solid and this decomposition should be endothermic rather than exothermic. The most effective polymers exhibit thermal decomposition which upon acid catalysis is shifted to lower temperatures and becomes more endothermic. These characteristics are effective because they interfere with heat transfer from the spall particle to the energetic solid. Knowledge of this mechanism has led to effective spall mitigation design rules for new formulations to mitigate the spall threat.

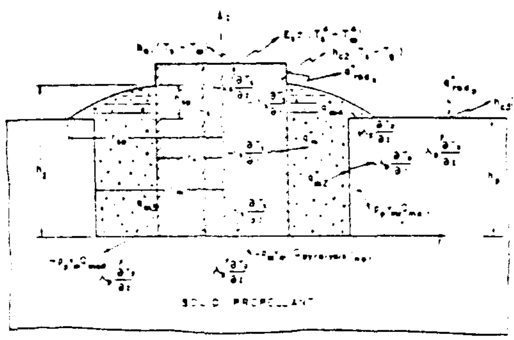

Figure 1. Thermophysical process involved in spall initiation of gun propellants

Hypervelocity Impact. The HVI mechanism, because it is very complex and not well understood, is currently the subject of intense research. CE HVI has been studied much more than KE HVI due to the experimental difficulties in working with the latter.

As a jet penetrates a granular propellant bed, an intense reaction occurs in the high pressure region immediately in front of the jet. Flash x-ray studies of this process by Watson and by Ramsey have shown that materials divide into two distinct types of behavior (Ref 13-14). In Type 1 materials, the reaction at the jet tip appears to decay significantly in velocity as it spreads radially; as the reaction proceeds away from the jet axis, it takes on many of the characteristics of a convective thermal combustion process where pressure, burning rate, surface area, and propellant energy are controlling factors. In Type 2 materials, the reaction proceeds in the radial direction at a sustained supersonic rate, though not necessarily at the velocity of a full detonation. Type 2 materials exhibit much greater violence of reaction.

Watson (Ref 14) has recently shown that the energy released in the blast wave is roughly proportional to the kinetic energy of the jet deposited in the propellant bed during the penetration process as shown in Figure 2. The kinetic energy is approximately $[V^2 \times D^2]$, where D is the final jet diameter after breakup. Type 1 behavior occurs when the response deviates markedly from this correlation. While many formulations have been shown to follow this relationship, it is not yet clear what chemical or physical properties of the propellant most affect this response or determine the transition point to Type 8 from Type 1 behavior. Thus, effective design rules to guide the development of new formulations to mitigate this threat have not been developed.

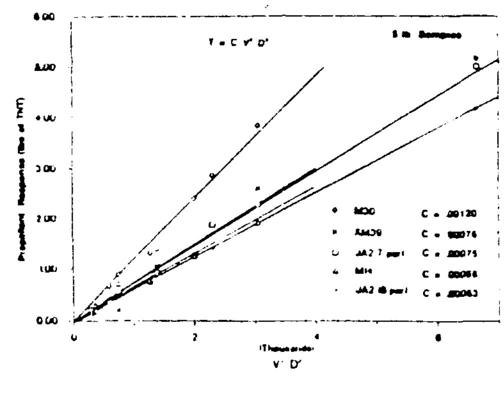

Figure 2. Energy release from granular propellant beds impacted by shaped charge jets of varying characteristics

There are some data which indicate that the mechanical properties of the propellant are important. Wise found that elastomeric materials were less violent than the more brittle plastic composite propellant formulations where energy, grain geometry and burning rates were similar (Ref 15). Both Ramsey and Liu have shown that the violence of response increases when HVI occurs at low temperatures (Ref 16-17). Thus a major thrust of new formulation development is to improve propellant toughness.

Limited experimental studies have been conducted on KE HVI. Lyman et al. (Ref 18) have recently conducted an experimental study which demonstrated the critical role of armor and storage on the response of 120-mm ammunition to this threat. Impact of a KE penetrator on target rounds with combustible cartridge case showed a mild reaction when the bare round was impacted and a slightly higher reaction when the cartridge was contained in its aluminium storage tube. When the KE penetrator passed through armor before impacting the tube and cartridge, the reaction gave a 2 to 4 times higher blast impulse. Results similar to those without armor, have been found for the response of 105-mm ammunition to 65-g fragments at velocities > 800 m/s. With the introduction of armor, the response seems to be dominated by prompt reaction to spall impact where the large volume of spall causes a much larger segment of the propellant to become involved in the reaction.

Evaluation Techniques. Two tests have been developed to examine a propellant's response to spall: The hot fragment conductive ignition test,conducted in a laboratory, and the CE generated spall range test. The former allows new formulations to be screened rapidly while final proof of a formulation's impact characteristics must be evaluated with the field test where the material is exposed to a threat spectrum similar to that expected on the battlefield.

Because of the complex mechanism, no useful laboratory scale test has been devised to rank the response of different propellants to HVI. Many larger scale experimental techniques have been developed, all of which involve the use of a shaped charge. These techniques differ principally in the

amount of material used and manner in which the energy released is measured. Currently the BRL is using the Plate-Pendulum test devised by Watson where the blast impulse from an impacted propellant bed is measure with a ballistic pendulum. The jet characteristics (diameter, tip velocity, residual energy) can be varied to characterize different formulations.

Because ammunition compartment survival is the ultimate pass/fail criterion for US tank ammunition, scaled compartment tests have been developed. These tests enable the system environment to be evaluated without the huge costs associated with full scale live fire testing. Unfortunately, results from these tests can only be related to the full scale results by empirical correlations. Efforts to develop useful modeling tools are underway.

Current State-of-the-Art Solid Propellants. The US has several propellants which have undergone extensive field testing to prove their ability to provide acceptable vulnerability levels on the battlefield. Tests include large scale component tests as well as full scale live-fire testing.

XM39 is a low vulnerability nitramine composite propellant developed to replace M30 propellant in the 105-mm M456A2 HEAT cartridge. It was designed to survive the severe spall impact threat environment within the M60 series tank.

JA2 is a conventional double-base formulation used in 120-mm tank cannon ammunition for the M1A1 tank. This propellant is very sensitive to the spall threat but this is not significant in the M1A1 where the ammunition is separated from the crew by blast doors. JA2 exhibits excellent response to HVI as measured by both the plate-pendulum and compartment tests.

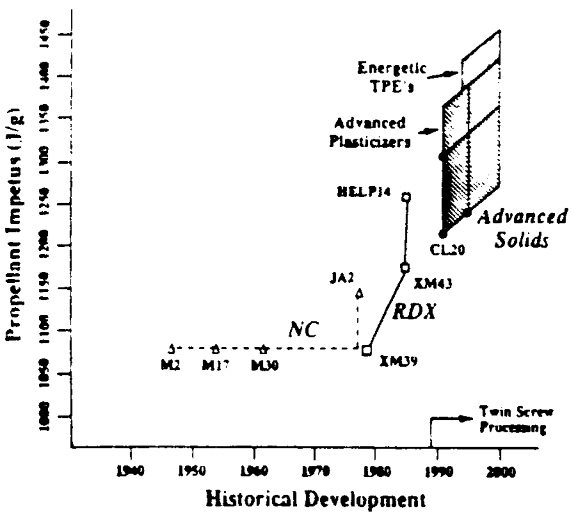

Figure 3. Recent trends in US gun propellant development.

M43 is a high energy, low vulnerability nitramine composite propellant developed for the 105-mm M900 APFSDS cartridge for the M1 tank. Like XM39, it is a nitramine composite propellant. It was designed to provide greater energy than JA2 together with a lower ballistic temperature coefficient. It maintains the HVI survivability characteristics of the ammunition compartment and exhibits high resistance to initiation by spall.

New Materials for Advanced Solid Propellants. The major emphasis in the development of new formulations has been on composites where an energetic solid is dispersed in a polymer matrix. Composites allow movement away from the limiting thermal sensitivity characteristics of nitrocellulose. Figure 3 shows trends in the development of new high energy low vulnerability propellants.

The search continues for new energetic solids which exceed the energy and density of RDX but with less thermal and shock sensitivity. Polycyclic and bridged nitramines as well as strained ring nitramines are families of new energetic materials with much promise. Examples of these include CL20 and TNAZ.

Many of the polymers used in rocket propellants have been evaluated in gun propellants. While properties have been attractive, the difficulty of controlling the cross-linking cure reaction during mixing and extrusion have not allowed these materials to be exploited.

Thermoplastic elastomers have great potential for several reasons: elastomeric mechanical properties, thermoplastic processing properties, great flexibility in achieving specific structure and chemical properties, etc. Non-energetic as well as energetic polymers are being evaluated.

Plasticizers are key ingredients because of their influence on energy, mechanical properties, and processing characteristics. A wide range of energetic and non-energetic materials are evaluated as part of our material development program. New materials exploit the nitramino and azido moieties for superior energy and reduced sensitivity relative to nitrato moieties.

Slowly, a set of design rules is being developed to streamline the rather empirical process of selecting the optimum plasticizer. One new and promising approach is the use of molecular modeling software to elucidate polymer-plasticizer interactions and evaluate the potential of new plasticizers.

Processing. The production process can greatly affect the vulnerability characteristics of a formulation through changes in microstructure and mechanical properties. Observations of individual grains with a scanning electron microscope have detected mix to mix variations in microstructure which correspond to observed changes in the vulnerability response to HVI. When the use of the emerging technology of twin screw extrusion becomes more widespread and combined with online measurement of rheological properties, the variations due to processing are expected to be significantly reduced.

The HVI response of a composite formulation has been shown to increase as particle size of the energetic solid increases. There are also some indications of particle shape effects. Great emphasis is currently being placed on studies in this area.

In summary, a prime objective of current work is to discover design rules that define the chemical and physical properties of a propellant so that it would be possible to specify propellant ingredients a priori in order to meet performance requirements and to mitigate a particular threat or spectrum of threats. While achievement of this goal is still far in the future, great progress has been made and extensive material databases have been established. Along the way, two generations of low vulnerability propellants have been developed.

4.1.2 Ballistic Applications

Ultimately, the performance of all gun launch systems is constrained by some maximum pressure or acceleration that can be tolerated by the payload and/or by some maximum pressure envelope that can be withstood by the gun tube. The former constraint is outside the scope of this discussion, but the latter is critical in the discussion which follows.

The basis of the interior ballistic cycle is a competition between the rate of gas generation (from burning of the propellant charge) and the rate of increase in available volume (a result primarily of motion of the projectile down the bore). Generate too much gas early in the ballistic cycle and the maximum pressure limit is exceeded; in practical terms, this places a limit on the initial burning surface. Later in the cycle, however, the projectile moves downbore, and a much higher mass generation rate is required to keep gun pressures from falling so low as to be ineffectual. Since propellant burning rates fall correspondingly with the falling pressure, the greatest possible burning surface area is required late in the ballistic cycle.

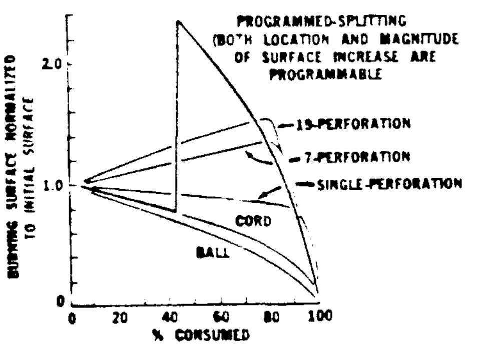

Figure 4. Surface area as a function of fraction burnt for various propellant geometries.

This requirement for a progressively increasing burning surface has led to the use of what are known as "progressive grain geometries." Single-perforated right circular cylinders have given way to seven-, nineteen-, and even thirty-seven perforated grains, the increasing numbers of perforations providing an increasing proportion of the total grain surface that grows with burn distance while the "degressive" exterior surface remains relatively unchanged. Surface profiles for several such geometries are shown in Figure 4, while their qualitative effect on gun performance is typified in Figure 5. Note that the increase in progressivity allows the effective use of greater total charge weights: more propellant can be consumed inbore to provide increases in muzzle velocity without a corresponding increase in maximum chamber pressure. A velocity increase of 2-3% has been demonstrated in numerous gun systems by replacing the standard seven-perforated grains with those of the nineteen-perforation geometry.

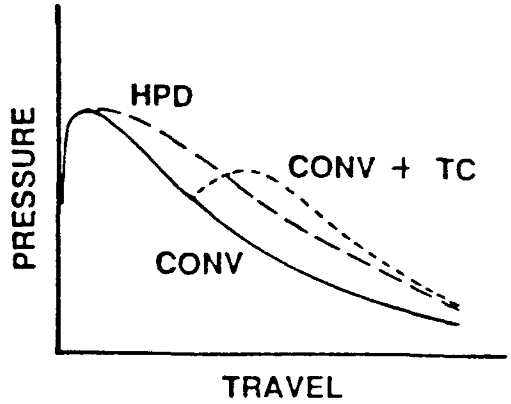

Figure 5. Projectile base pressure vs travel for various propellant geometries.

There are practical limits to this philosophy of grain design, and while large (perhaps monolithic) grains with very many perforations are under investigation, production of such configurations are difficult. Current efforts address both extrusion and casting techniques, but efforts remain in the early development stages. Advantages, however, in terms of both loading density and burning surface progressivity are obvious. An alternate and perhaps even more attractive approach to providing a highly progressive, monolithic propelling charge involves the use of very high burning rate (VHBR) propellants, and is discussed in a subsequent section of this paper.

<u>Deterred or inhibited propellants.</u> Chemically deterred ball propellant has long been used in small-caliber guns (Ref 19). Application to large caliber propellant configurations focuses on the use of deterrents or inhibitors on the outer regressive surfaces of multi-perforated grains to reduce or even eliminate burning in these regions, thereby increasing the net effect of burning on the progressive perforation surfaces. Unfortunately, deterrent technology remains as much an art as a science, both in terms of ballistic analysis and in terms of production and quality control. Further, the concept is generally not attractive in existing gun configurations with limited chamber volumes, where the loss in total energy associated with the deterred regions cannot be offset by increased total charge weights. Inhibitor coatings, both simpler in concept and perhaps more universally applicable, are receiving considerable current attention, but, as of yet, present formidable production challenges.

<u>Programmed energy release concepts.</u> Returning to Figure 4, we note that classical approaches to achieving progressivity fall far short of the optimum profile dictated by the volume liberated as the projectile moves downbore. Particularly desirable would be a programmed energy release propellant grain, for which an increase in mass generation rate could be programmed to commence at the

most efficient time in the burning process. Thus, a very high loading density charge could be employed without over-pressurization early in the cycle, yet the programmed increase in energy release after peak pressure could assure total burning of the charge before projectile exit from the gun tube.

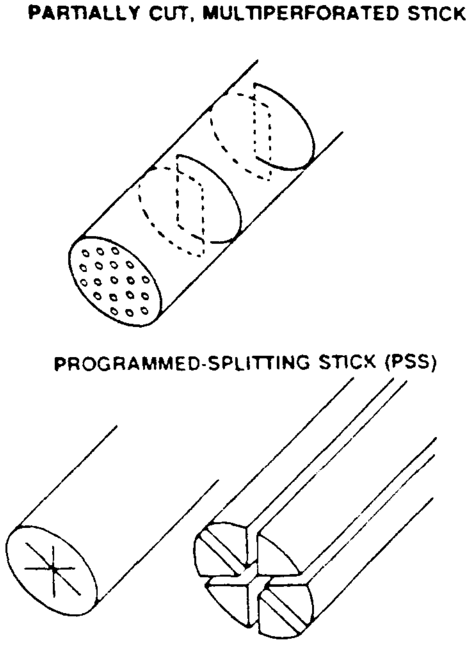

Figure 6. Example of novel grain geometries

Figure 6 depicts a family of such concepts involving either chemical or physical programming of energy release. The layered propellants (cylindrical or scroll) would consist of lower burning rate and/or energy propellants on outside surfaces, to which the burning would be limited until after peak pressure. Then, a significant increase in energy release would be programmed to commence with burning of the higher burning rate and/or energy core propellant. Conceptually, any number of layers could be employed to achieve a desired energy release profile. Practically, however, even two layers have been difficult to produce and current efforts focus on the physical analog, known as programmed splitting stick propellant (Ref 20). This version of programming relies on a significant increase in burning surface after peak pressure, achieved when the burning of the outside lateral surface of the stick reaches an embedded array of slits, the core separates, and the flame envelops the additional surfaces (see Figure 4). Any of these concepts can be designed to lead to a second ...in to peak pressure, as shown in Figure 5, with increased downbore pressures accompanying the consumption of increased charge weight.

Significant performance gains (+ 5-10% in muzzle velocity) can be expected from this family of concepts even in volume-limited gun designs, since a very high loading density is achievable using these essentially solid cylinders. Even larger gains can be expected in systems currently limited by maximum pressure or acceleration rather than by available chamber volume. The largest gains are, of course, obtainable in new gun systems designed to take full advantage of such charge designs.

Consolidated charges. It is worth mentioning briefly that the application of the consolidated charge concept to large caliber guns continues to receive some interest though with unremarkable success to date (Ref 21). This concept is based on achieving higher loading densities by compacting conventional granular propellants through the use of solvation and/or heat. The initial reduction in available surface resulting from the intimate contact between grains followed by a subsequent increase in surface are as the compacted charge deconsolidates during burning may also be a means of increasing progressivity of the overall charge. While extremely attractive in computer simulations, the concept is hampered in reality by an incomplete understanding of and control over the deconsolidation and flamespreading events and by manufacturing and reproducibility problems. No successful large caliber demonstration of significant performance increases via this technique is known to these authors. Current Air Force and Army efforts to develop consolidated charge munitions in smaller caliber, however, appear to making substantial progress.

VHBR monolithic propellant charge. Higher performan solid propellant charges require more total energy in the gun chamber AND proper programming of the energy release to maintain downbore pressures without increasing the maximum breech pressure. The VHBR monolithic propellant charge (shown below) employs a very high burning rate propellant, allowing the use of much thicker burn distances (webs) without leaving unburned propellant at the end of the interior ballistic cycle (Ref 22).

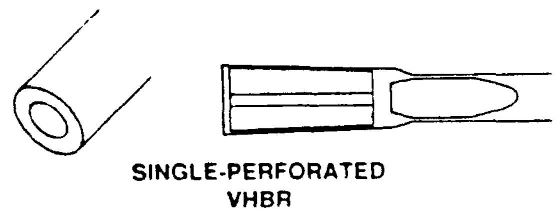

Figure 7. VHBR monolithic propelling charge.

The propellant can then be cast into a cartridge case as one large, single-perforation grain (rather than hundreds or even thousands of much smaller granules), with the outside surface inhibited from burning by the case itself. Since the charge consists of a single grain, a very high loading density can be achieved (in fact, the perforation configuration can be optimized with respect to any projectile intrusion). Further, since it burns only on the inner surface, a very progressive geometry is achieved.

Solid propellant traveling charge. As mentioned above, higher performance requires more total energy AND proper programming of the energy release. To achieve muzzle velocities in excess of 2 km/s, very high propellant charge to projectile mass ratios (C/M) are required, posing numerous burdens on the system, not the least of which is a very large breech pressure in order to communicate adequate downbore pressures to reach such velocities

An alternative to increasing the mass of the propellant charge in the chamber is to affix part of the charge to the projectile itself (Ref 23). Thus, gases are generated at the base of the projectile, and pressure losses from gun chamber to projectile base are not suffered. However, the mass of the traveling charge itself must be accelerated along with the rest of the projectile. Therefore, a tradeoff exists that does not favor use of the traveling charge until very high velocities are required. Further, severe mechanical as well as combustion requirements are placed on the traveling charge. Current interest centers on use of a VHBR (very high burning rate) traveling charge (shown below), so that simple geometries may be used which provide adequate strength to survive the launch environment and transmit the accelerative forces to the projectile.

Figure 8. VHBR traveling charge

Temperature-compensation techniques. An extremely attractive approach to improved performance is the removal of propelling charge temperature sensitivity, allowing operation under all ambient conditions at the same maximum chamber pressure as that normally associated only with hot firings (Ref 24). Accompanying increases in muzzle velocities at ambient conditions are on the order of 3-7% for most high performance gun systems. Successful techniques must reliably and reproducibly counter the usual increase in reaction kinetics (which translates into propellant burning rates) associated with increases in initial propellant temperature. Always conditioning the stowed ammunition at the high temperature limit on board the weapon system could provide an easily achievable and fail-safe technique for extracting the benefits of temperature insensitivity. To date this approach has not been accepted.

Chemical additives, long used in the rocket propellant industry to alter burning rates and influence temperature sensitivity, have not been successfully developed for gun propellants. Yet, it is well known that some gun propellant formulations exhibit significantly greater temperature sensitivity than do others. Successful development of chemical control of temperature sensitivity would provide one of the easiest means of improving overall system performance possible.

A [illegible]ary mechanism may be superimposed on the normal combustion process to achieve a net burning rate at ambient temperatures similar to that normally occurring only at the hot limit. Possible approaches include the use of microwaves to rapidly heat the propellant in situ to the hot limit just before or during firing, external gas injection to raise burning rates for cool charges, and laser stimulation to alter reaction rates.

Certain composite propellant formulations which are easily deformable under mechanical loads have exhibited significant reductions in temperature sensitivity under certain ignition/loading conditions. It is postulated that localized ignition may lead to severe compaction of the propellant bed, deformation of grains, and occlusion of some of the available burning surface during flamespread. Since the mechanical properties of the grains are highly temperature dependent, this effect may be much more pronounced at high temperatures, delaying the onset of combustion for much of the charge and significantly reducing the increase in pressure otherwise expected for hot charges. Successful exploitation of this behavior would require reliable control of the process and appropriate optimization of grain design.

Microcracks are introduced into ball propellants during the rolling process. Their presence apparently reduces temperature sensitivity by leading to an increase in burning surface when fired cold. Cold conditioning results in enhanced brittle fracture of the microcracks in the propellant during the early burning process. Again, reliable control is required for full exploitation.

Deconsolidation of a compacted charge can significantly impact the progressivity of the overall charge. The temperature dependence of this deconsolidation process, a result of the mechanical resilience of the compacted matrix, can reduce or even eliminate the temperature sensitivity of the base propellant.

A variety of control tube primers have been suggested. An example of the concept is shown in Figure 9. They provide different initial projectile positions and velocities, depending on temperature, prior to ignition of the main charge - thereby altering early projectile travel and countering the temperature sensitivity of performance that would otherwise occur. A number of projectile options are conceivable which could alter early motion as a function of temperature through such mechanisms as changes in available volume or bore resistance. A breech mechanism could be designed that senses propellant temperature and alters available volume accordingly. Alternatively, it could sense pressurization rate or level and provide a rapid change in volume. A similar device could be incorporated into the chamber wall, either locally or distributed circumferentially as a layer of some compressible material.

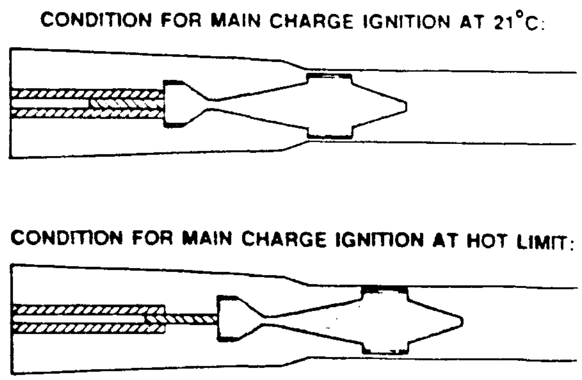

Figure 9. Temperature compensation using control tube primer.

4.1.3 Vulnerability Implications of Advanced Propulsion Concepts.

Each of these advanced propulsion concepts have different and largely unknown influences on munitions survivability. Based on the mechanistic insights gained, it is possible to make some projections about the IM aspects of these advanced concepts. For all of these concepts, sensitivity to spall impact initiation should be dominated by the basic chemical and thermophysical properties of the formulation used. Thus the following discussion will focus on the HVI response.

Progressive Grain Geometries. Propellant grain geometry has been shown to have a pronounced effect on HVI response. For granular charges, blast impulse decreases as grain size increases and then increases again after going through a minimum. This effect appears to be controlled by surface area and fracture susceptibility at smaller grain sizes while critical diameter for supporting a detonation reaction appears to be important at larger diameters. These effects are formulation and threat dependent, of course. Also, for some formulations, it has been observed that stick propellant geometries can result in a increase in response level; this may be due to the ability of the reaction to spread more rapidly through the bed. Large monolithic grains may present a particular challenge because of their large diameter and because the burning rates of the formulations used may have to be higher than for conventional grain designs.

Deterred or Inhibited Propellant. The presence of a deterrent or inhibitor could be beneficial to those propellants which exhibit the more benign Type 1 behavior because of the similarity of this process to a convective combustion wave where reduced burning rates should have a retarding effect. Of course, this effect could be mitigated depending on the delay until the higher energy inner core is reached and it is even possible for the inner core propellant properties to grossly overwhelm the inhibitor effect. As these concepts are used to increase the charge loading density, HVI blast response should be expected to increase if greater amounts of energy are available.

Programmed Energy Release Concepts. For the layered concepts similar considerations should hold as for the deterred or inhibited grains. The programmed splitting stick charge may show some benefit because of the low amount of initial surface area as well as the greater mechanical strength of the sticks.

Consolidated Charges. The effects for consolidated charges are expected to be similar to the deterred or inhibited grain case. The low initial surface area of the charge in its consolidated form and the poor mechanical coupling for shock transmission between base ... may be beneficial. Experimental data are few and conflicting at this time. More extensive experiments are to be conducted.

VHBR Monolithic Propelling Charge. The higher charge loading density and higher burning rates associated with this concept should present severe challenges to ammunition survivability.

Solid Propellant Traveling Charge. Application of this concept requires materials with very high burning rates. Like the VHBR case above, this concept may present a serious survivability challenge. However, this may be mitigated if the traveling charge is limited in size/mass.

Temperature Compensation Techniques. The mechanical techniques for temperature compensation should have little effect on survivability. Chemical additives which boost low pressure burning rates should adversely affect the response to HVI as should the concept of storing propellants at their upper operating temperature.

Because of the US requirements for IM, all new propulsion concepts will undergo thorough evaluation in the exploratory and advanced development stage and many of the above projections will be evaluated.

4.2 REGENERATIVE LIQUID PROPELLANT GUNS

Liquid propellant guns (LPGs) have been the focus of periodic research efforts in the United States since the late 1940's (Ref 25). A wide variety of gun concepts and liquid propellants have been investigated in the course of this research which, until recently, has met with only limited success. Over the last ten years, LPG research in the US has been focused on the regeneratively injected gun concept utilizing a hydroxylammonium nitrate (HAN) based liquid propellant. This gun and propellant combination has recently been selected as the gun propulsion system of choice for the Army's Advanced Field Artillery System, AFAS.

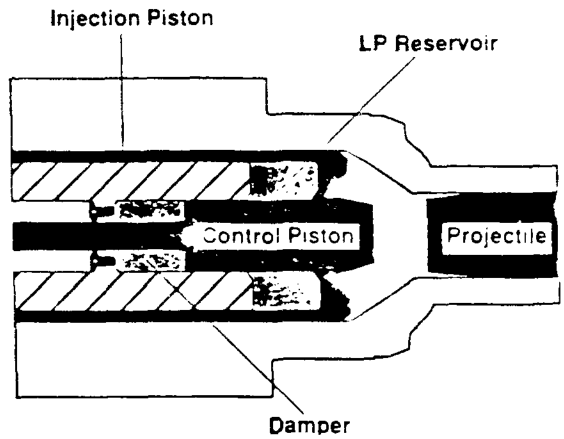

Figure 10. Regenerative liquid propellant gun concept.

The regenerative liquid propellant gun (RLPG) interior ballistic cycle is controlled by the injection of the LP into the combustion chamber (Fig. 10) and, thus, by the motion of the regenerative piston. In the simple in-line piston RLPG depicted in Figure 10, the injection orifices are initially sealed the LP is loaded into the propellant reservoir, and a projectile is placed at the entrance to the barrel. A pressure versus time characteristic of a simple in-line RLPG is presented at Figure 11. The IB process is initiated by an external igniter charge which pressurizes the combustion chamber. This gas pressure forces the injection piston rearward, compressing the LP in the reservoir. The differential area of the injection piston from the combustion chamber to the reservoir serves to amplify the combustion gas pressure, producing a higher pressure in the

LP reservoir and, thus, providing the pressure required to break the orifice seals and inject propellant into the combustion chamber. The second phase of the IB process is an ignition delay, during which the piston continues to move rearward, injecting additional LP which accumulates in the combustion chamber. This accumulated LP then ignites and rapidly burns (phase three), bringing the chamber to operating pressure and accelerating the piston to its maximum velocity. Phase four is often characterized by a pressure plateau in the simple in-line RLPG configuration. This plateau is interpreted as a quasi- stable equilibrium in which the volume increase in the combustion chamber and the flow of combustion gases down tube are balanced by the combustion of freshly injected LP. Phase four ends with the completion of piston travel and propellant combustion. The final phase is the usual expansion of combustion gases after all-burnt.

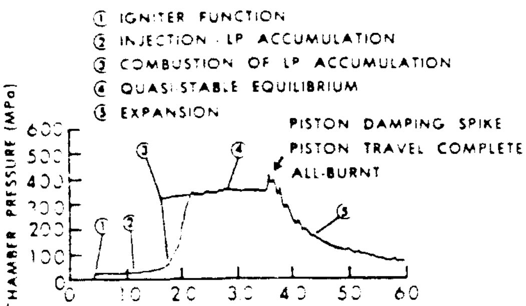

Figure 11. Typical pressure-time history for a regenerative liquid propellant gun.

The US candidate liquid propellant, recently designated XM46, is a stoichiometric mixture of hydroxylammonium nitrate, water and triethanolammonium nitrate. The formulation and chemical properties of this propellant are described in detail in the literature (Ref 26). XM46 has been shown in testing to possess a variety of desirable characteristics, however, in the context of this report, the key characteristics of the LP are the difficulty with which it is ignited if not confined, its relative insensitivity to impact and shock and its favorable response in a variety of hazards and insensitive munitions tests (Ref 27-31).

The motivation behind the recurring efforts to develop LP guns over the last forty years is the potential for realizing the pervasive systems benefits offered by a fluid propellant. These potential benefits include reduced facilitization and propellant costs, increased logistic efficiency and effectiveness, increased safety throughout the military system including reduced vulnerability on the battlefield, si[illegible]ed gun automation, and increased gun system performance and effectiveness. Thus, the successful fielding of an LP gun system would have a major impact on all aspects of the military system, beginning at the production level.

The current liquid propellant gun program in the United States was initiated in the late 1970's, with General Electric taking the lead in gun design and testing and the Army assuming responsibility for IB investigations and propellant development. Since that time, several thousand test firings have been conducted in a variety of calibers up to 155 mm. Two generations of 155 mm RLPGs have been built and tested; the first generation fixture was designed to provide ballistic data in large caliber, while the second was designed to demonstrate most of the functional characteristics of a fieldable gun system. Interior ballistic investigations, both experimental and theoretical, have been conducted in parallel with the large caliber gun engineering and test efforts. These experimental investigations have lead to an increased understanding of the RLPG process which has been incorporated into interior ballistic computer models (Ref 32-33). These models accurately describe the RLPG IB process and are routinely used in data analysis, gun design and new concept evaluation (Ref 34-36).

In the liquid propellant area, a broad research and development program has been conducted encompassing: basic chemistry; extensive physical, chemical and hazards characterization; production process development; and applications systems studies and analyses. As a part of this effort, extensive hazards, insensitive munitions and vulnerability testing has been conducted as noted above. These tests have, of necessity, addressed only fundamental LP properties and the characteristics of the LP in surrogate transportation and vehicle storage containers. At present, the propellant has passed all the required tests of the Joint Services Insensitive Munitions Criteria, with the exception of a sympathetic detonation test in which the interpretation of the limited test results does not lead to a clear conclusion. Additional testing is planned to address this question. While the results of these tests have tended to confirm the potential of the LP as a reduced sensitivity material, they have also emphasized the systems nature of the problem, i.e. the need to treat the propellant, the packaging and storage concepts, and the vehicle design as an integral system in order to realize minimum system vulnerability.

The key technical and engineering challenges for the liquid propellant gun fall generally into gun and propellant categories. In the gun area, the presence of high frequency pressure oscillations in the combustion gases is the key near term technical challenge. These oscillations are not related to the lower frequency, longitudinal pressure waves which are responsible for breech blows in conventional solid propellant guns. The primary concern raised by the presence of these oscillations is their effect on sensitive projectile components, e.g. fuzes, rather than the potential for combustion anomalies or gun damage. In the longer term, the key developmental engineering challenge of the RLPG is reliability in a field environment. This issue will be the focus of intense engineering effort as well as test and evaluation during the development process. In the propellant area, the primary challenge is the engineering and design of the components and infrastructure which will facilitate successful integration of a liquid propellant into the field Army. These include not only production facilities, storage and transportation containers, handling equipment, etc., but also the new procedures and doctrine necessary to optimize operations with a liquid propellant. Again, in the context of this report, emphasis must be given to systems design in order to exploit the reduced sensitivity characteristics of the LP and optimize safety and vulnerability reduction.

The regenerative liquid propellant gun has been designated as the system of choice for AFAS, however, there

are substantial technical engineering challenges to be overcome before fielding such a system. Therefore, LP appears, at present, to be the most mature of the novel gun propulsion concepts being pursued by the Army. As the AFAS component maturation program proceeds, the identified challenges will be addressed and it is probable that, given adequate resources, they will be satisfactorily resolved. Therefore, it seems highly possible that fielding of an LP artillery system could begin around the year 2000.

4.3 ELECTROTHERMAL-CHEMICAL GUN PROPULSION

Electrothermal-chemical (ETC) guns are a broad class of hybrid gas dynamic gun propulsion concepts which utilize a combination of electrical and chemical energy sources. These concepts have their origins in the pure electrothermal (ET) propulsion concepts which appear in the hypervelocity literature of the 1960's and again in the late 1970's and early 1980's in the work of Goldstein and Tidmann of GT Devices, Inc. The "pure" ET propulsion concept involves the use of electrical energy to create a high temperature plasma which mixes with and vaporizes an inert working fluid to generate the high pressure gas needed to accelerate a projectile.

The original motivation for the ET propulsion concept was increased muzzle velocity. Indeed, much of the early support for this work was provided through the SDI program in which ultra-high velocities were the objective. Since the sole energy source for the propulsion process is electrical, materials which produce low molecular weight gas when vaporized can be used. Thus, the ET propulsion concept can be viewed as a single stage, electrically powered light gas gun, with the attendant advantages of such systems in the hypervelocity regime. Systems evaluations of tactical applications of the ET concept quickly lead to the realization that electrical energy requirements are of the same order as those for electromagnetic guns, thus making power component and system technology a key driver and reducing the attractiveness of ET concepts in the tactical arena for any near-term applications.

In the mid-1980's, due in large part to the rationale outlined above, GT Devices under contract to the Army and FMC Corporation using IR&D funding began exploring hybrid electrothermal propulsion concepts in which some portion of the energy was provided by an energetic working fluid or propellant. A schematic depicting the interior ballistic process of these concepts is presented in Figure 12. The basic configuration is quite similar to that of a bulk-loaded liquid propellant gun. The energetic propellant initially fills the combustion chamber between the breech and projectile base. The electrical energy is employed to generate a plasma in a capillary which is located external to the combustion chamber, usually attached to or part of the breech mechanism. The process is initiated by the application of the high voltage across a fine fuse wire connecting electrodes at either end of the capillary. The fuse is vaporized, generating a plasma through which additional current is passed, further heating the plasma. As a result of the high pressure generated in the capillary, hot plasma with temperatures on the order of 20,000 - 30,000 K, is the injected into the propellant. The mass lost through plasma injection is replaced by ablation of the material lining the plasma capillary. The plasma temperature and pressure in the capillary are then maintained by the resistive heating of the electrical current flowing through the plasma.

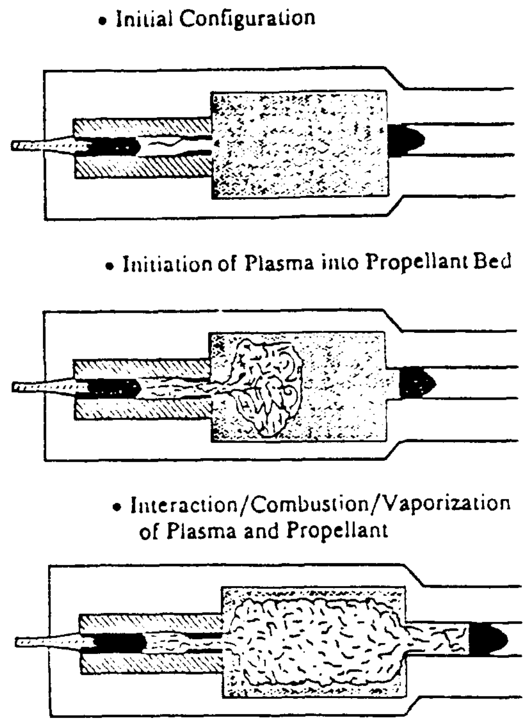

Figure 12. Interior ballistic process for electrothermal gun propulsion concept.

In the mid-1980's, due in large part to the rationale outlined above, GT Devices under contract to the Army and FMC Corporation using IR&D funding began exploring hybrid electrothermal propulsion concepts in which some portion of the energy was provided by an energetic working fluid or propellant. A schematic depicting the interior ballistic process of these concepts is presented in Figure 12. The basic configuration is quite similar to that of a bulk-loaded liquid propellant gun. The energetic propellant initially fills the combustion chamber between the breech and projectile base. The electrical energy is employed to generate a plasma in a capillary which is located external to the combustion chamber, usually attached to or part of the breech mechanism. The process is initiated by the application of the high voltage across a fine fuse wire connecting electrodes at either end of the capillary. The fuse is vaporized, generating a plasma through which additional current is passed, further heating the plasma. As a result of the high pressure generated in the capillary, hot plasma with temperatures on the order of 20,000 - 30,000 K, is the injected into the propellant. The mass lost through plasma injection is replaced by ablation of the material lining the plasma capillary. The plasma temperature and pressure in the capillary are then maintained by the resistive heating of the electrical current flowing through the plasma.

The ETC interior ballistic process is quite complex, involving an initial mixing of plasma and propellant to initiated decomposition, followed by the reaction of the bulk

of the propellant in a highly unstable hydrodynamic environment driven by the injection of additional plasma. This environment appears similar to that encountered in the bulk-loaded liquid propellant gun, and it is reasonable to anticipate that phenomenological descriptions of the IB processes will, therefore, be similar.

The attractive features of this concept are: the potential reduction in required electrical energy in comparison to the pure electrothermal and the electromagnetic propulsion concepts; the increased loading density possible through bulk-loading of the propellant; the potential to utilize non-traditional propellant chemistries which may provide increased propellant specific energies and/or reduced propellant vulnerability; and the potential to utilize electrical energy to tailor the combustion of the propellant and thereby tailor the projectile base pressure to increase gun performance. The rationale for the recent interest in the ETC propulsion concept in the United States is based on these potential benefits. If these benefits can be realized, significant performance increases will be possible within existing gun envelopes. In particular, it has been suggested that increases in muzzle energy of 50-100% are possible in existing 120 mm and 155 mm gun systems with relatively modest investments of electrical energy. The potential for substantially reducing electrical power requirements is very attractive since both dependence on advances in power technology and the vehicle integration burdens would be reduced, thus potentially reducing time for realization of practical system.

These potential benefits are all based, at least in part, on the assumption that electrical energy can be utilized to control the combustion of the propellant (either through direct control of the propellant reaction rate, or control of mixing and surface generation, or both) (Ref 37). It has been shown that a relatively small amount of electrical energy can be used to initiate the ETC process. It is assumed that the application of additional electrical energy (through a plasma) during propellant combustion can be utilized to control propellant combustion. At present, it is not clear to what degree this control can be realized nor is it clear how much electrical energy would be required to achieve that control. After maximum pressure, it appears possible to maintain projectile base pressure by the addition of plasma energy to heat the combustion gases and thus realize an increase in gun performance. The energy required, which can be estimated in a simple thermodynamic analysis, is large and efficiency decreases rapidly in the latter stages of projectile travel.

Ballistic control and electrical energy requirements have been two of the primary ETC research issues in the US since about 1986 (Ref 38). GT Devices and FMC Corporation have remained the primary innovators in ETC technology, though recently other private firms have begun work in the area.

GT Devices, in conjunction with General Dynamics Land Systems, has focused their efforts on low molecular weight propellants and reduction of the electrical energy requirement in an ETC gun to less than 5-10% of the total required energy. This of course means that 90-95% of the energy is supplied by chemistry. In this effort, they have explored a variety of nontraditional propellants, as well as alternate methods to generate plasmas and to use them to control the interior ballistic process.

FMC Corporation has continued investigations of their CAP_{TM} concept, though they have also explored propellants other than their original hydrogen peroxide - hydrocarbon bipropellant mixtures. Both groups have progressed toward their objectives under contracts with a variety of Government agencies as well as their own resources. Army-sponsored efforts have been focused mainly on anti-armor applications, though there is interest in other possible tactical missions. However, the Army's goal of demonstrating controllable, repeatable ballistics with an acceptable propellant while achieving a significant performance increase has yet to be realized. In parallel with, and in support of, contractor efforts, the Army has initiated experimental and theoretical interior ballistic research projects. The objectives of these projects are to identify novel propellant materials for use with an ETC gun, to experimentally investigate the ETC interior ballistic process in order to identify key parameters and develop and understanding of component processes, and to develop computer models of the IB process. Related programs have been initiated by the Defense Nuclear Agency for artillery applications and the US Navy as a future Close-in Weapon System (CIWS), i.e. a potential Phalanx replacement (Ref 39).

The technical challenges faced by the proponents of the ETC concept are outlined above. Control of the interior ballistic process, i.e. control of propellant combustion, must be demonstrated. This requires, as a minimum, tailoring of the pressure rise rate to limit projectile jerk and achieve the desired maximum pressure. Performance improvement may also require control of the IB process after maximum pressure to permit tailoring the pressure profile. In any case, a substantial performance increase, i.e. higher muzzle energy or velocity than is possible with a solid propellant in a given gun configuration, must be demonstrated for tactical applications of an ETC concept to be attractive. Repeatability sufficient to meet Army dispersion and accuracy requirements must also be demonstrated. A predictive modeling capability is desired to support ballistic research and rational gun design. Further these criteria must be met using a propellant which is fieldable in the Army system. This discussion does not address issues related to the electrical power supply, nor does it address issues generally addressed later in the development cycle. However, these issues require consideration as the technology begins to mature.

To this point, the potential impact of ETC technology on the insensitive munitions issue has not been addressed except to note that the potential for using non-traditional chemistries might lead to propellants with reduced sensitivity (Ref 40). Given the very early stages of ETC research, it is difficult to make substantive statements regarding the characteristics of a system yet to be defined. This is also the case for the electrical power supply since little is known about the sensitivity and vulnerability of existing components, much less the incre energy and power density components required in the future for tactical applications of electric guns.

In summary, the ETC propulsion concept holds potential for substantial systems benefits if the key technology issues can be resolved satisfactorily. Existing data is inadequate to support rational projections of technology maturation, however, if the technical objectives of the Army's ongoing ETC program are met over the next few years, development of an ETC gun system during the first decade of the next century may well be possible.

4.4 ELECTROMAGNETIC GUN PROPULSION

The other propulsion technologies, including the hybrid electrothermal propulsion, discussed in this paper rely on the expansion of pressurized propellant gasses. An electromagnetic (EM) gun uses instead intense magnetic fields applied locally to a projectile, requiring pulses of electrical power as the ultimate energy source.

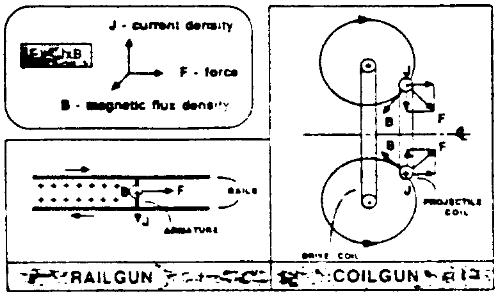

Figure 13. Generic geometries, magnetic fields and forces in the railgun (left) and the coilgun (right)

EM guns fall into two basic classes, railguns and coilguns. These differ in the geometry of achieving confined magnetic fields, and of coupling the resultant forces to achieve projectile acceleration (Ref 41), as schematically shown in Figure 13. As a rule, railguns are conceptually and geometrically simpler, and have lower impedance (i. e., require higher current and lower voltage for a specific propulsion task). They have received far more developmental attention, despite the potential for greater energy efficiency from coilguns. Coilguns become more attractive at larger scale due to more efficient coupling and the difficulties associated with precise switching may impose velocity limits lower than those for railguns.

Prospects for EM guns are intrinsically linked to the technology for generating their power requirements. A megajoule-scale muzzle energy requires gigawatt-scale pulses for the milliseconds of the acceleration event. Power supply approaches include mainly rotating machines which provide pulses from inertially stored energy, and capacitor-based pulse forming networks.

A substantial literature is available to describe the evolution of the requisite component technologies over the past decade. Proceedings of the five meetings of the biannual "Electromagnetic Launch Symposium" are conveniently accessible (Ref 42-46). The rapidly growing body of European activity was represented at a recent Symposium in London (Ref 47).

Because they require no propellant medium, EM guns can in principle deliver velocities well above those of any other guns. Velocities up to 6 km/sec have been achieved with railguns in numerous laboratories (Ref 42-47). Energy efficiency is not strongly dependent on muzzle velocity until near 6 km/s, where in practice new mechanisms apparently limit both efficiency and achievable velocity.

A primary benefit of electric guns is the potential for substantially enhanced system performance. Claims regarding this enhancement have two major themes: Increased projectile velocity will improve lethality against armored targets, increase the air defense keep-out range, and extend the range of fire support weapons. The absence of energetic propellant will also benefit vulnerability and logistics.

Development of an EM armament system will need to marry a number of advanced components and technology areas: hypervelocity operation, new types of gun barrels, new hypervelocity projectiles, and electrical power supply componentry. The pacing technical challenge is reduction in system mass and volume, which is dominated by the electrical power supply. There has been great improvement during the past five years, but substantial further reduction is required.

The US Army Armament Research, Development and Engineering Center (ARDEC) leads the US program for tactical weapon applications. Armor defeat is the focus application driving choices of component technology requirements. The program aims to field electric armament systems in the 2010+ timeframe, and will involve a choice between electromagnetic and electrothermal technology in the interim. The Strategic Defense Initiative Organization (SDIO) program is motivated by strategic and theater missile defense systems.

Two 90 mm laboratory railguns with a 9 megajoule (MJ) muzzle energy capability are operational. The one at the University of Texas Center for Electromechanics (UT/CEM) is powered by six homopolar generators, and is used to develop the technology for solid projectile armatures. The other, at the Maxwell Labs-operated Green Farm site, has a capacitor-based power supply, and fires with arc armatures. Experiments are underway at both sites to establish a data base in the 2 to 4 km/sec velocity regime. They address mass vs velocity tradeoffs for armor defeat, and support 90 mm projectile development tests.

Design and fabrication of 9MJ "SLEKE" (sabot-launched electric gun kinetic energy) projectiles is being performed contractually at the Kaman Corp and the LTV Corp. The efforts involve variations in sabot and armature configuration, as well as in penetration mechanism (solid vs segmented rod configurations). Major performance issues are launchability, sabot discard, tipoff, velocity reproducibility, and flight and terminal effects. Railgun testing of initial designs is underway at interim energy levels.

Hardware is coming on line which takes the technology out of the laboratory, in two separate developments that address first-order integration issues: (1) A self-contained, multiple shot "skid" railgun system weighing 25 metric tons will be tested next year. Its 90 mm railgun is powered by a "compulsator" (compensated pulsed alternator), and is being fabricated at the University of Texas Center for Electromechanics. The compulsator will deliver 30 MJ to the railgun breech, a factor-of-ten advance over any prior machine of its size. (2) FMC is completing a stand-alone repeatable battery/capacitor-based power supply, in a transportable trailer-like housing, which will also be ready for testing in 1992. This "Pulse Power Module" (PPM) is designed to deliver 8 MJ pulses to an electrothermal-chemical (ETC) load,

but applies to EM gun development also, as a first step at reducing total pulse forming network (PFN) energy density.

The tactical program is structured for a follow-on advanced technology demonstration (ATD) to begin in late 1995. Entrance criteria have been defined for the ATD, and a component maturation program is in place to meet them. This includes the technologies required for (1) power system downsizing to 10 kJ/kg delivered energy density for the TOTAL pulse power system; (2) optimization of hypervelocity utility, particularly for the anti-armor application; and (3) development of barrel/armature interfaces (and solution of related impediments) that enable robust, high-performance weapon systems. The Army receives planning and execution assistance in this component maturation program from its Federally Funded Research and Development Center (FFRDC), the Institute for Advanced Technology at the University of Texas. Cross-links between the Army tactical program and the SDIO strategic one have been identified, and will be exploited.

Improved survivability and important logistics benefits are expected to follow from the replacement of vulnerable chemical gun propellants with diesel fuel or its equivalent. This will apply on the battlefield and throughout the manufacturing and logistics chain. The tradeoff is the need for robustness and survivability in all the components of an armament system far more technically complex than conventional propellant guns.

The electrical power system, while having lower energy density (and therefore more "manageable" vulnerability issues than energetic materials), is of special concern. As the energy density of capacitors, batteries, inductive devices, or rotating machinery increases, their vulnerability and damage potential is likely to increase as well. More specific comments in this area must await the component maturation which will develop specific power componentry.

There are prospects for decreased under-armor volume, and/or increased stowed projectile load. Presuming their potential benefit can be developed and optimized, hypervelocity projectiles are smaller and lighter than conventional ones, and they will not have big propellant-filled cartridges attached to them. These benefits multiply in a system sense because they also mean reduced ammunition handling and loading requirements. An important technical uncertainty at this point is the battlefield effectiveness of lighter, smaller projectiles with kinetic energy equal to a heavier, larger projectiles.

Reduced recoil will be associated with EM guns for two reasons: for a given projectile kinetic energy, smaller hypervelocity projectiles have lower momentum transfer. In addition no propellant gases contribute to recoil in an EM gun. The anticipated factor-of-two recoil reduction will reduce the recoil system and, hence, the total system weight.

Additional prospects for increased system effectiveness involve synergism with the advantages of all-electric drive tank systems, and with EM armor protection technologies. A reduction in conventional blast and smoke signatures can also be expected.

In sum, electromagnetic gun propulsion promises significant performance advances and benefits over conventional armament systems. Moreover, significant space and weight reduction are projected if and when the necessary power supply downsizing has been achieved. The monumental challenge of developing, integrating and weaponizing the component technologies will certainly involve serious new difficulties, some of them not obvious now.

4.5 IN-BORE RAM ACCELERATION FOR GUNS

Higher performance chemical propellant charges require more total energy in the gun chamber AND proper programming of the energy release to maintain downbore pressures without increasing the maximum breech pressure. To achieve muzzle velocities in excess of 2.5km/s, very high propellant charge to projectile mass ratios (C/M) are required, posing numerous burdens on the system, not the least of which is a very large breech pressure in order to communicate adequate downbore pressures to reach such velocities. Electric propulsion concepts, particularly electromagnetic, offer real hope for providing a nearly uniform acceleration profile, thus removing the requirement for very high breech pressures, but, as we have seen, currently carry with them significant other burdens.

An alternative approach to increasing the mass of the propellant charge in the chamber is application of ramjet technology to inbore propulsion. The ram cannon accelerator, depicted schematically in Figure 14, consists of a projectile, resembling the centerbody of a ramjet, traveling through a gun tube which acts as the outer cowling. The tube is filled with a gaseous fuel/oxidizer mixture, and the combustion process travels with the projectile, generating thrust which accelerates the projectile down the tube to very high velocities. Thus one has the major advantage of a traveling charge without the burden of accelerating the propellant with the projectile. Projectile velocities reaching the Chapman-Jouguet detonation speed of the mixture have been theoretically associated with a subsonic, thermally choked combustion mode; University of Washington tests have yielded velocities in excess of 2.6 km/s with 70 g projectiles in a 38-*mm* bore tube using this mode (Ref 48-49).

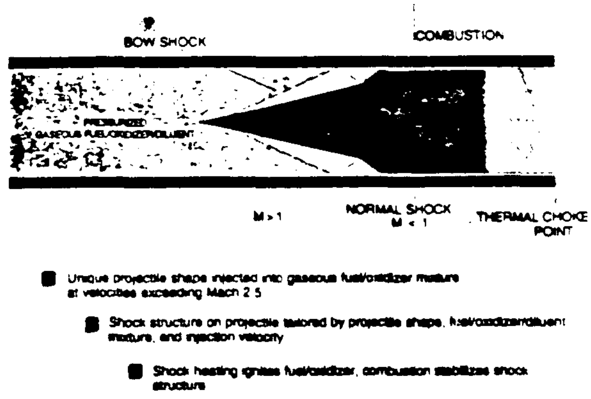

Figure 14. Ram cannon accelerator concept.

Several investigators predict velocities as high as 9 km/s from various detonative combustion modes theoretically

associated with the ram accelerator concept (Ref 50). Experimentation in this area, only now beginning, is of potential interest to communities addressing problems associated with hypervelocity penetration studies, the National Aerospace Plane (NASP), and potential strategic defense missions.

Efforts to develop large-caliber ram accelerators are currently ongoing at the Franco-German Research Insitute in St. Louis, France, and at the Ballistic Research Laboratory, Aberdeen Proving Ground in the US (Ref 51-52). In addition, NASA is sponsoring an experimental program to exploit detonation modes of ram/scram propulsion at velocities above 4 km/s in a medium caliber launcher.

Numerous technical problems, both of a fundamental and practical nature, remain to be solved before ram acceleration becomes a serious contender in the field of tactical gun propulsion. Understanding, control, and optimization of the fluid dynamics/reaction kinetics in this environment present a formidable challenge. Incorporation of this emerging technology into a practical weapon with acceptable safety, reliability, and survivability characteristics as well as performance levels offers even greater uncertainties. Assessment of the IM characteristics for such accelerators has yet to receive serious attention.

5. CONCLUSIONS

Advanced gun propulsion efforts in the US clearly focus on both improved ballistic performance and increased survivability. Truly insensitive munitions remain an ideal to be sought but never fully attained. Realistically our objective are less-sensitive munitions when compared with conventional propellant munitions. Both certain liquid propellants and HELOVA propellants offer chemical approaches to less-sensitive munitions. For electromagnetic guns, the intrinsic hazard of energetic propellants is replaced by increased amounts of less sensitive diesel fuel carried on-board and the presently unknown hazard/vulnerability characteristics of high energy/high power storage devices. This approach promises at least in principle major decreases in system vulnerability. Electrothermal/Chemical gun propulsion is exploring alternative chemistries and unique physical approaches to achieve significant reductions in munitions sensitivity. Power train hazard issues, while qualitatively similar to those of electromagnetic guns, are expected to be quantitatively less significant due to the reduced electric power and energy requirements. The in-bore ramjet cannon is clearly in a very early experimental stage and little can be said definitively about its systems potential nor its associated hazard issues.

Current US insensitive munitions test methodology is likely to become more sophisticated with increased emphasis on evaluation of system "sensitivity" against expected threats rather than simply isolated munitions sensitivity. This requires realistic descriptions of the likely threats that munitions/systems are expected to survive. These are often difficult to define and consensus is sometimes difficult to achieve. Yet this information is critical to any analysis process and often will determine the specific test methodology to be employed for the evaluation of a given systems vulnerability.

System survivability can be significantly increased if less-sensitive munitions, packaging, storage location, compartmentation, internal protection, and external armor protection are combined in synergistic fashion. Much progress is being made in understanding at least qualitatively the design guidelines for improved synergism. It is in the context of an integrated approach to system vulnerability reduction, that threat-specific "insensitive" systems are possible, even with "less-sensitive" munitions carried on board.

6. ACKNOWLEDGEMENTS.

The authors would like to thank Dr. Ron Derr for suggesting this AGARD paper be presented summarizing current advanced gun propulsion work in the USA. We are grateful to Mr. P. Serao from Picatinny Arsenal who was very helpful in providing background on Army policy and directions. We thank Dr. R. Frey for presenting a technologist's perspective on insensitive munitions issues.

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Discussion

QUESTION BY DEFOURNEAUX, NIMIC: You said that electric guns would not solve the problem of warhead vulnerability. What about using an electric gun to accelerate (up to Mach 2, say) a solid fuel ramjet-sustained projectile fitted with a fuel-air warhead? This system would require no gunpowder, no rocket propellant (the ramjet uses atmospheric oxygen) and no high explosive (same reason). This is partly a joke, but it might constitute a line of thought.

ANSWER: But then NIMIC would be out of business! More seriously, this is an insensitive, truly "insensitive" approach looking for an application in the far future. Technically, solid fuel ramjet projectiles suffer from difficult launch and flight problems which have not yet been overcome. Fuel air explosives are limited primarily to soft target kills. And the risks in Electric Guns development are still formidable. Great line of thought!

MBB-DEVELOPMENT OF INSENSITIVE PBX-CHARGES

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Introduction:

The designation "sensitivity" commonly used for general test results obtained on high explosives respectively high explosive charges comprises a variety of different test procedures applied on high explosives resp. H.E. charges.

With this variety in potential test procedures, however, different high explosive and H.E. charge characteristics are determined as they are also applied for varying conditions and statements. In general, the individual test procedures and test methods must be familiar to permit recognition and judgement of statement value, statement meaning and a correct assignment of the factor achieved, as in most cases the designation chosen is the same, that is "sensitivity".

Sensitivity Categories

The various test procedures are subdivided and contemplated in accordance with their statement capacity regarding:

- Handling Sensitivity (UK: sensitiveness)
- Survivability
- Initiability (UK: sensitivity).

The aspect "handling sensitivity" is the most critical one, as when handling high explosives resp. H.E. charges and processing them, reaction should be avoided to the utmost extent during raw material handling, preparation and processing of the same and when carrying out a normal transport.

Regarding the munition "survivability" during its utilization it is essential to preclude reaction even under extremely strong loads and extreme environmental conditions. The corresponding trials simulating launch acceleration resp. extreme stresses, such as high altitude drop tests, form part of this criterion. For several tests H.E. reaction may even be admissible, but if possible, in a very moderate way as for example during the fuel-fire-test. In practice, such stresses represent in most cases "rare exceptions".

Notwithstanding this, reaction shall not resp. must not occur, even not partial detonations. A detonation always brings about destruction of the direct surroundings and endangers persons within the closer area.

"Initiability" means the minimum pressure and also the minimum projectile velocity at which detonation occurs in full extent. For test purposes, the limit between reaction and detonation is determined, whereby this detonative induction can also be desirable. With stimuli by far inferior all the same, more or less violent transformations occur.

Types of Stress:

The various stress types are subdivided into five categories:

- mechanical
- electrical
- shock wave
- projectiles
- thermal.

There is a variety in different stress types and test installations for the above mentioned categories which are only in part standardized internationally. Within the individual stress types, these stimuli often also render varying statement values regarding a.m. sensitivity categories.

It would certainly be beyond the scope of this paper to list and describe all standardized tests and the large number of tests which have been conducted by several individual institutions.

But practically any test, which, in a historical point of view certainly bases on events, has its meaning even if it is presently not very informative as regards to all material systems and configurations of use.

Test Matrix

Figures 2) and 3) show the problems representing the basis for at least the major part of the various test methods and procedures.
On one hand, varying quantities are planned and used for the tests. Reaction probability, however, is in many cases also a function of the test quantity provided.

Condition of test specimen and surrounding also has an essential effect on the resulting reaction intensity. It is necessary to distinguish on one hand between raw material in a powder state and granulated material and on the other hand between HE charge types - in most cases available in a solid state - manufactured by casting, pressing, extrusion etc. and most of all to determine if they undergo tests without a casing, that is without confinement or if they are comprised in a casing, which means confined.

Charge size and confinement exert considerable influence so that a number of tests should be carried out only on the actual warheads. As, however, good comparison capacities with various material systems are required, the test vehicles used are chosen by random.

Another aspect is that applying a load, normally no reaction is desirable which is most of all important for the handling of high explosives.

In case excessively strong loads are applied, for example placing the munition in a fuel fire under which reaction resp. burning-off of an energetic substance is unavoidable, a moderate, smooth burning, but no violent reaction, most of all no detonation with blast and fragmentation effect to the surrounding is admissible. This means that for the survivability tests the reaction shall be very moderate and mild, if it is unavoidable.

This is most of all important when the H.E. charge mass is high as this renders a big radius for the destructive effect. This is not as critical for smaller H.E. charge masses as their total energetic resp. performance capacity is also minor.

The first part (fig. 4 to fig. 21) comprises the test and inspection procedures admissible for H.E. charges which are explained and assigned to the individual stimuli types.

The second part (fig. 22 to fig. 38) gives explanations on specific new definitions for tests to accept less sensitive high explosive charges or, more precisely, less sensitive warheads.

First Part - General Tests

The tests for the handling safety render the sensitiveness of the samples. As a result, we normally get the threshold between no reaction / reaction. Specimens in a powder state are generally used for these tests (fig. 4).

With the survivability tests we obtain the vulnerability of the HE charges or of the ammunitions. The tests are generally conducted on the charges or ammunitions and the threshold is no reaction or low order reaction, compared with high order reactions.

The initiation tests show us initiability - i.e. how easily the high explosive can be initiated. The threshold will be defined between "reaction" and "full detonation". The samples are in this case commonly high explosive charges.

The samples are either powdered or solid and their stimuli thresholds depend on a lot of parameters (fig. 5), such as type of HE or composition, phlegmatization of granulates, bulk density or porosity, grain size or grain size distribution, also on the quantity and certainly, very much on the confinement.

All the tests for the different stimuli can be categorized in (fig. 6):

- mechanical tests
- electrical (electrostatic) tests
- shock tests
- projectile impact tests
- temperature tests.

The different tests for each category - except for electrical tests - are summarized in tables. The individual tests for each category are listed, the samples generally used as powder (P) or HE-charge (C) are indicated, further, if the test is useful for handling sensitivity (Ha) or for survivability (Su) or initiability (In) and, finally, the test will render the limit between no reaction / reaction (R) and reaction / detonation (D).

The first example is given in fig. 7 for the mechanical tests. The individual tests which are not very famous such as Skid, Susan, Spigot and Gun Set Back test are sketched in fig. 8.

The same procedure is repeated for the shock tests (fig. 9). Description is given more in detail for the instrumented gap test, with which it is also possible to obtain the build-up distance as a function of pressure, the so-called pop-plot diagrams (fig. 11), and also for the modified gap test with typical results (fig. 12) and the multi gap test (fig. 13). The different projectile impact tests are listed in fig. 14. The p^2t law is demonstrated for a well detonable high explosive charge - PBX 9404 - with electric gun or flying plate, results see (fig. 10).

Results of flat faced projectiles against PETN are given in fig. 15, with shaped charge jets against composition B charges in fig. 16.

The various temperature tests are listed in fig. 17. These tests can be physically subdivided in: - Constant temperature tests
- Increasing temperature tests
- Constant heat capacity.

The sample must be carefully arranged in a confinement to provide always the same heat conductivity and well reproducible results, as shown in fig. 18, with the One Dimensional Time to Explosion test (ODTX). The fuel fire test is also a typical test with increasing temperature as a function of time. The sample should be a real warhead (fig. 19). Surprising is that a real brightly gluing sphere of 20mm diameter is not able to bring a cast TNT/RDX charge to a violent reaction (fig. 20).

A summary is given in fig. 21 on how to better distinguish between tests and their purpose:
- Sensitivity tests with intended non reaction
- Survivability tests with non high order reaction and
- Initiability tests to determine the limit between reaction and detonation.

Second Part - MIL-STD-2105A Tests

The specifications for tests on insensitive high explosives (less sensitive high explosives) acc. to MIL-STD-2105A carried out on 19-1-1990 are illustrated in this chapter (fig. 22).

The verbal descriptions of the individual explosive reaction levels (fig. 23) are visualized in fig. 24 with regard to pressure output and fragmentation of the casing.

A different response category was used in UK for RATTAM tests (fig. 25 and fig. 26). But after the presentation of my paper I have learnt by a letter that now UK is using very similar ranking response criteria to MIL-STD-2105A.

The item numbers and test sequence for MIL-STD-2105A are again shown in fig. 27. The partially verbal description on the fast cook-off test or fuel fire test is given in fig.28.

The slow cook-off test is, in the opinion of the author, an extremely rare phenomenon. On the other hand, this test is expensive when being conducted on real warheads. Maybe it should be used on standard configurations as a screening test for HE materials, but not really be seriously taken into account as a safety or survivability test (fig. 29).

The drawing is a little bit improved for the bullet impact test (fig. 30).
The fragment impact test requires fragment velocities of 8300ft/sec. with fragment masses of 16g (fig. 31). These very high fragment velocities are not very realistic. Only one warhead should exist with these static fragment velocities. But here we should take a more realistic parameter pair in fragment mass, resp. velocity. Survivability tests should cover all accidents which happen exclusively with 99% or max. 99.9%, but never with 99.999999%.

The procedure applied for the sympathetic detonation test is clear (fig. 32 and fig. 33).

Shaped charge tests are described too much in detail with regard to shaped charge geometry and specific shaped charge liners. The important parameters for the reaction threshold of SC charges are jet tip velocity and jet diameter. Generally it is not possible to receive identical raw materials and production procedures throughout the individual NATO countries and thus liners which are required as indicated in the above document (fig. 34, fig. 35, fig. 36 and fig. 37). Furthermore it is very difficult to create a high explosive so little sensitive that it will not react violently by the impact of the 81mm shaped charge jet with tip velocities in the range of 9mm/us or reduced to 6 - 8 mm/us by cover plates.

Summarizing the tests for less sensitive high explosives (insensitive high explosives) acc. to MIL-STD-2105A:
- Fast cook-off test (fuel fire test), bullet impact test, sympathetic detonation test and spall impact tests are realistic tests for ammunitions.

- Fragment impact tests with 16g and 8300 ft/s are overdriven.
- Slow cook-off tests take place only very rarely.
- The shape charge tests as described above cannot really be reproduced because of the too specific descriptions given for the individual parts.
  But generally, the test with the 81mm shaped charge is an unrealistic goal for warheads.

General Tests

Handling Sensitiveness
Survivability
Initiability (UK: Sensitivity)

Specific New Insensitivity Tests

Summary

Figure 1

Test - Matrix

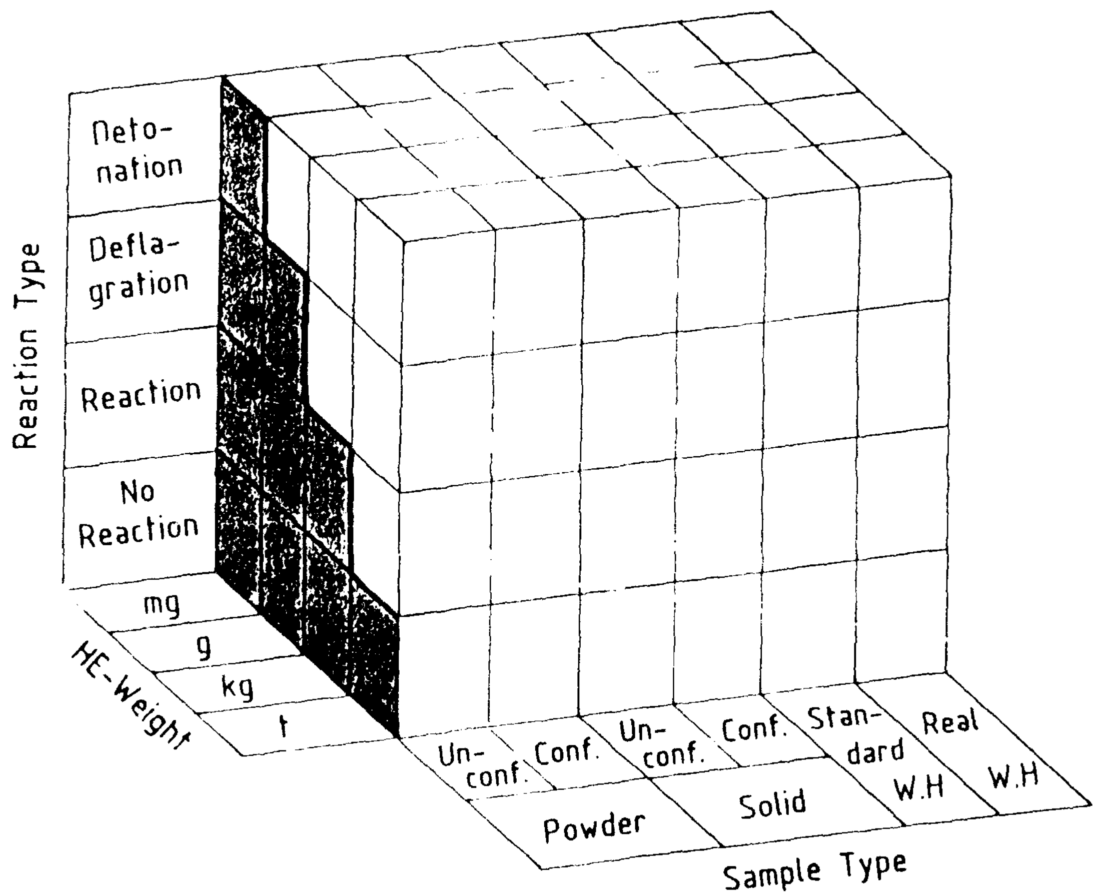


Figure 2

Tests for HE-Charges

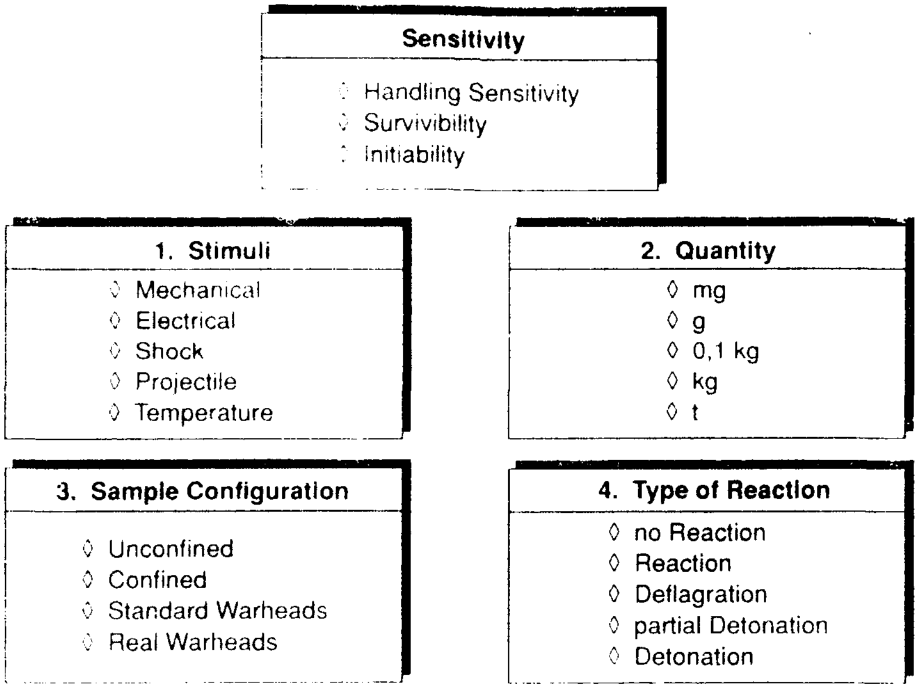


Figure 3

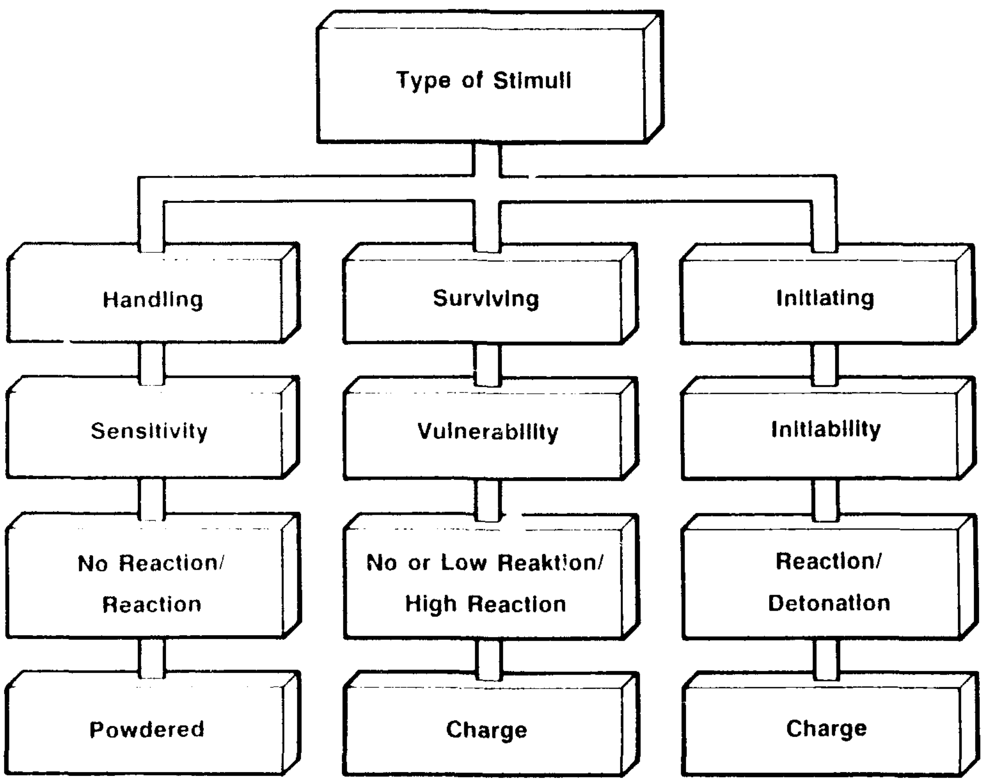


Figure 4

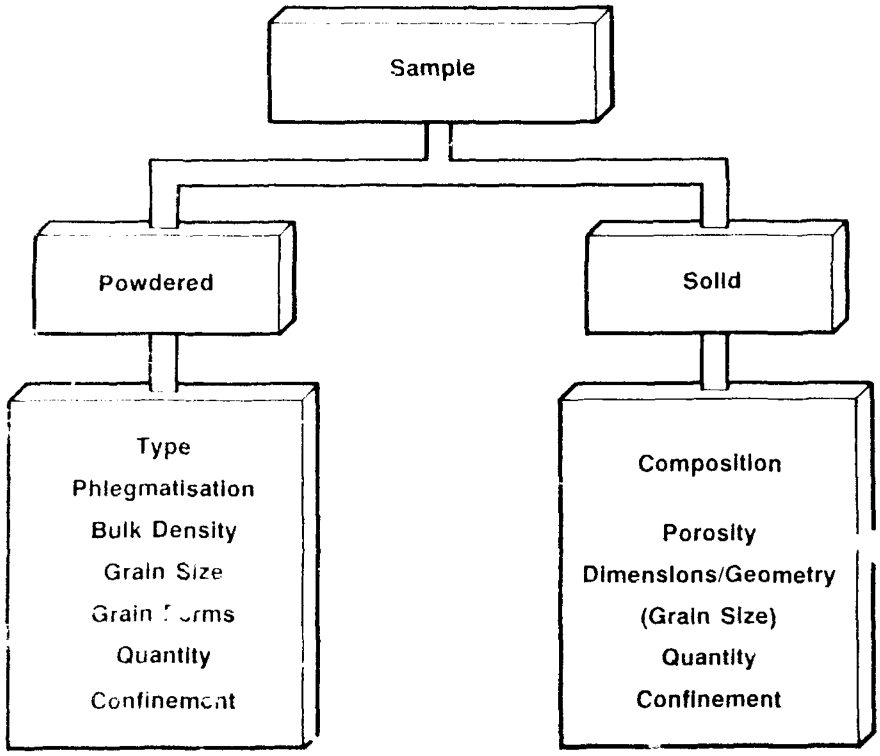


Figure 5

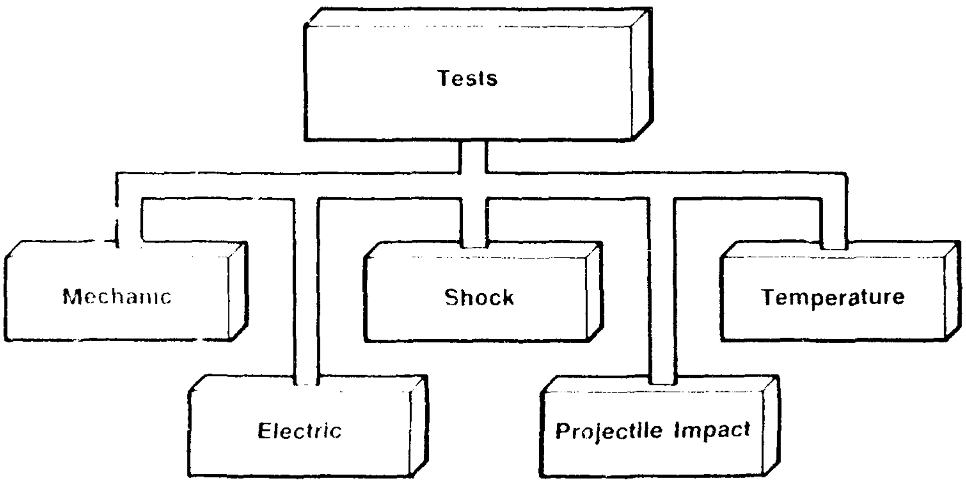


Figure 6

Mechanical Tests

Test	Probe	Reaction Mode	Reaction Type	Result
Impact *1	P	Ha	R	(Joule)
Friction	P	Ha	R	Rel. Units
Vert. Acticator	C	Su	R	(Joule)
LABSET	C	Su	R	Force
Skid *2	C	Su	R	(Energy)
Susan	C	Su	R	(Blast)
Spigot	C	Su	R	Go / No-Go
Gun Setback	C	Su	R	a (m.s⁻²)

*1 Drop Hammer

*2 Oblique Impact

Figure 7

Mechanical Survivability Tests

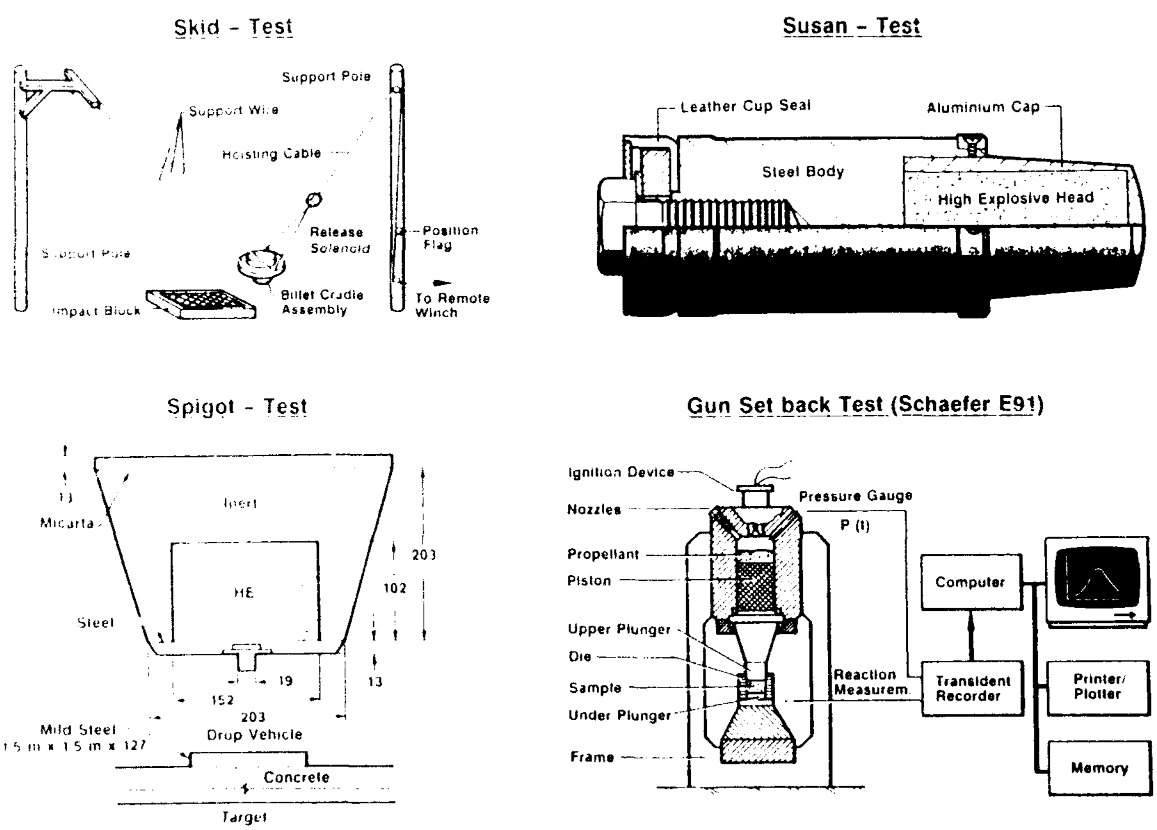


Figure 8

Shock Tests

Test	Probe	Reaction		Result
		Mode	Type	
Cap	C	Su	R	Go / No-Go
Prim. Charge	C	In	D	mg PETN.Sylg.
Gap	C	In	D	p_{min}
Instrum. Gap	C	(Su)/In	(R)/D	t, d=f(p)
Aquarium *1	C	Su	R	$\int p(t)\,dt$
Mod. Gap	C	Su.In	R/D	p_{min}
Multi Gap	C	Su	R	$n \cdot p_{min}$
Wedge	C	In	D	(t), d=f(p)

*1 Low Amplitude Shock Initiation

Figure 9

One Dimensional Tests

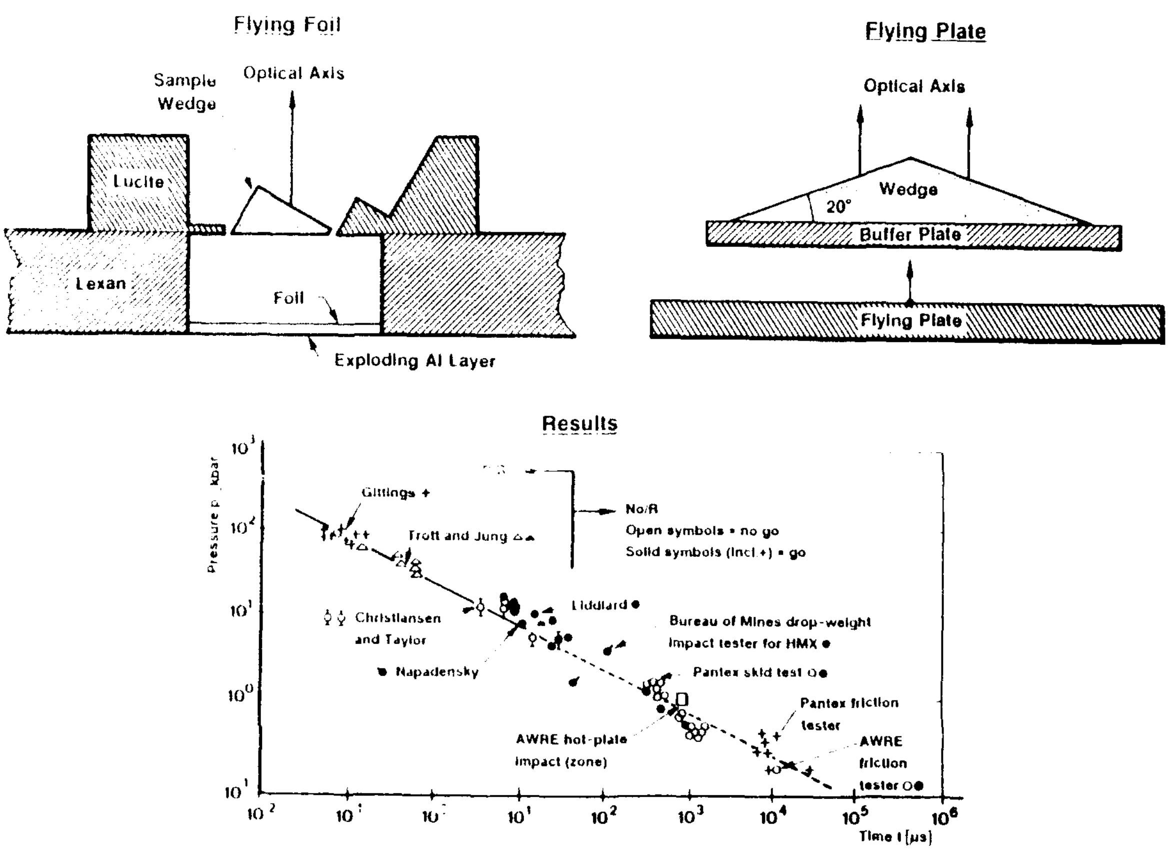
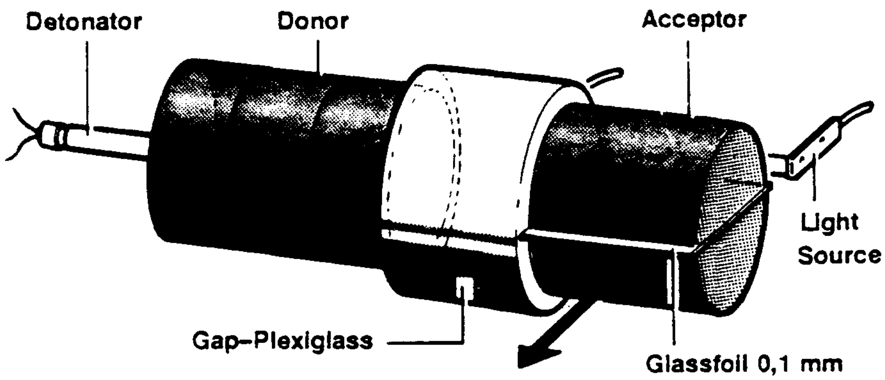


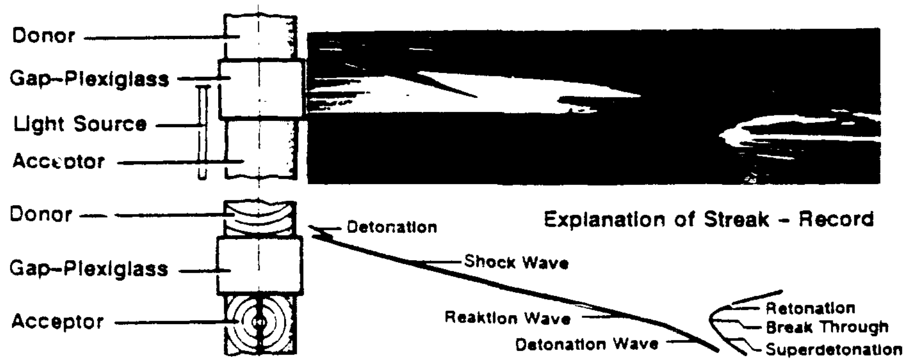
Figure 10

Instrumented Gap Test

Test Set - up



Streak Record



Results

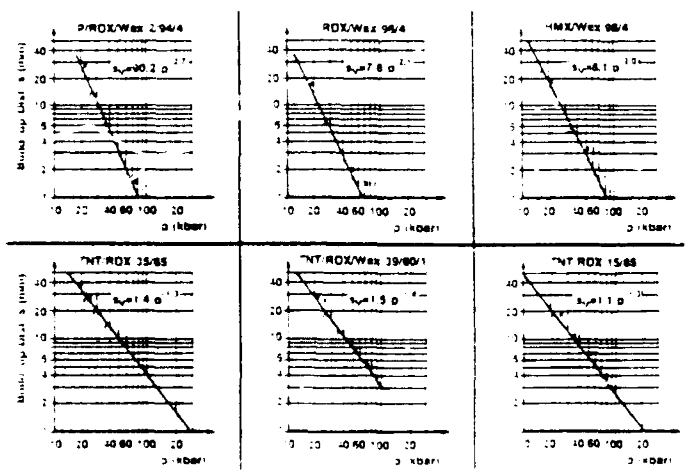


Figure 11

Modified Gap Test

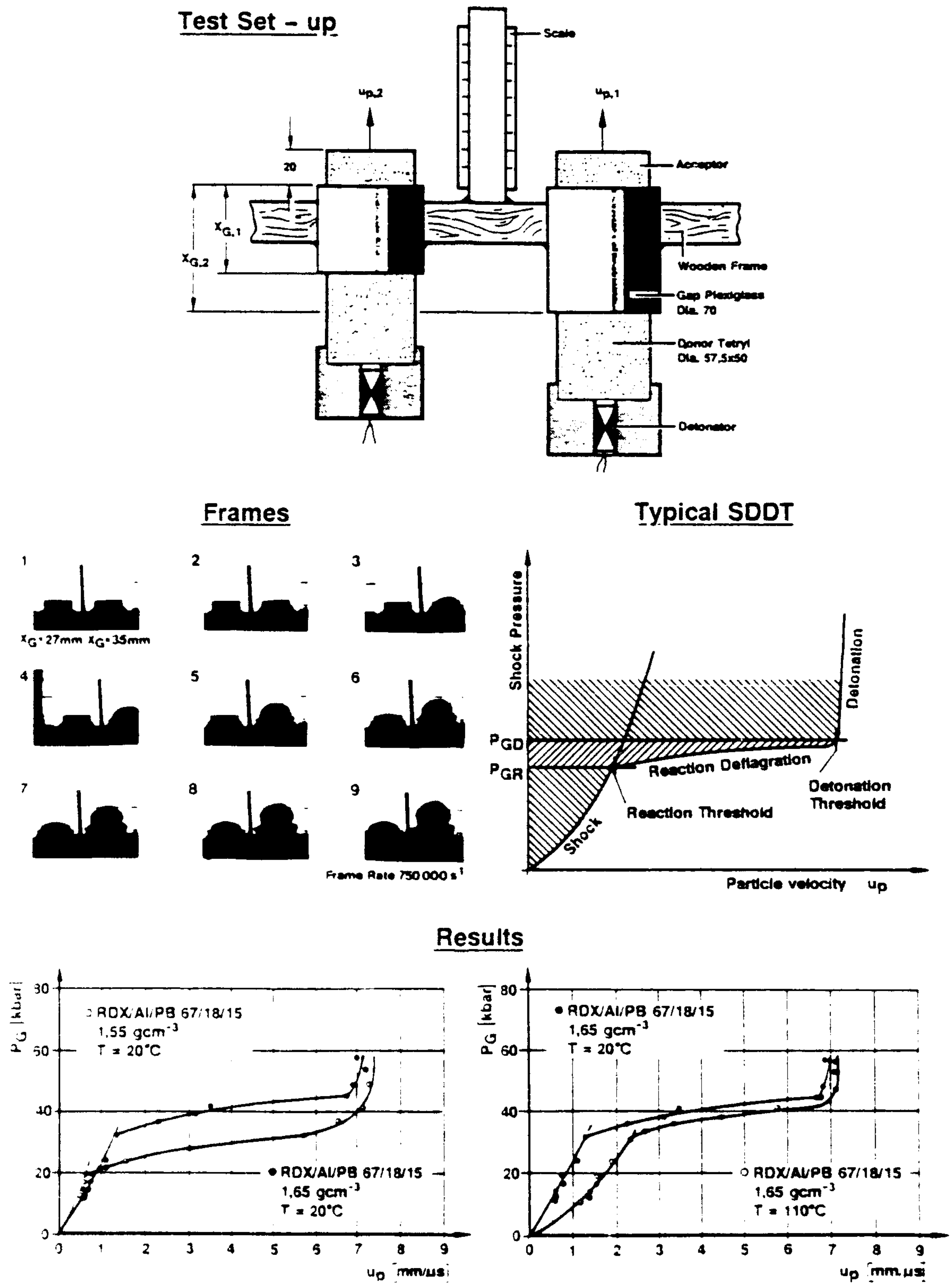
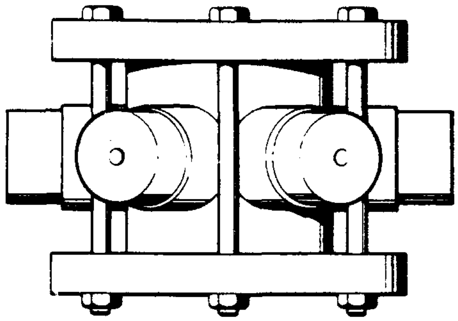


Figure 12

Multi Gap Test

Test Set - up



Results

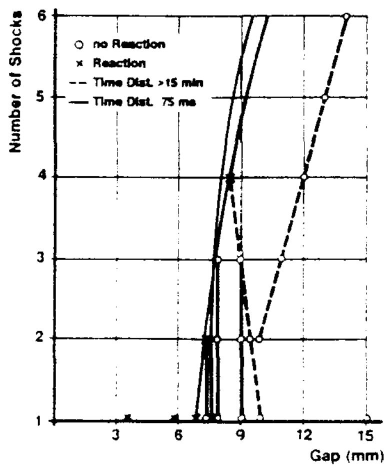


Figure 13

Projectile Impact Tests

Test	Probe	Reaction		Result
		Mode	Type	
Flying Foil	C	In	D	t, d=f (v_i, t_i)
Flying Plate	C	In	D	t, d=f (v_i, t_i)
Bullet Impact 5.56,7.62,12.7	C	Su	R	Go No Go
Flat Faced Projectile	C	In	D	$v_{i,\,cr}$
Instr. F. F. P.	C	Su	R D	t, d=f(v_i)
Instr. Shaped Charge Jet	C	Su	r d	t, d=f(v_i, Dia)
Multi-Fragments or Bullets	C	Su	R	n v_i

Figure 14

Projectile Impact Tests

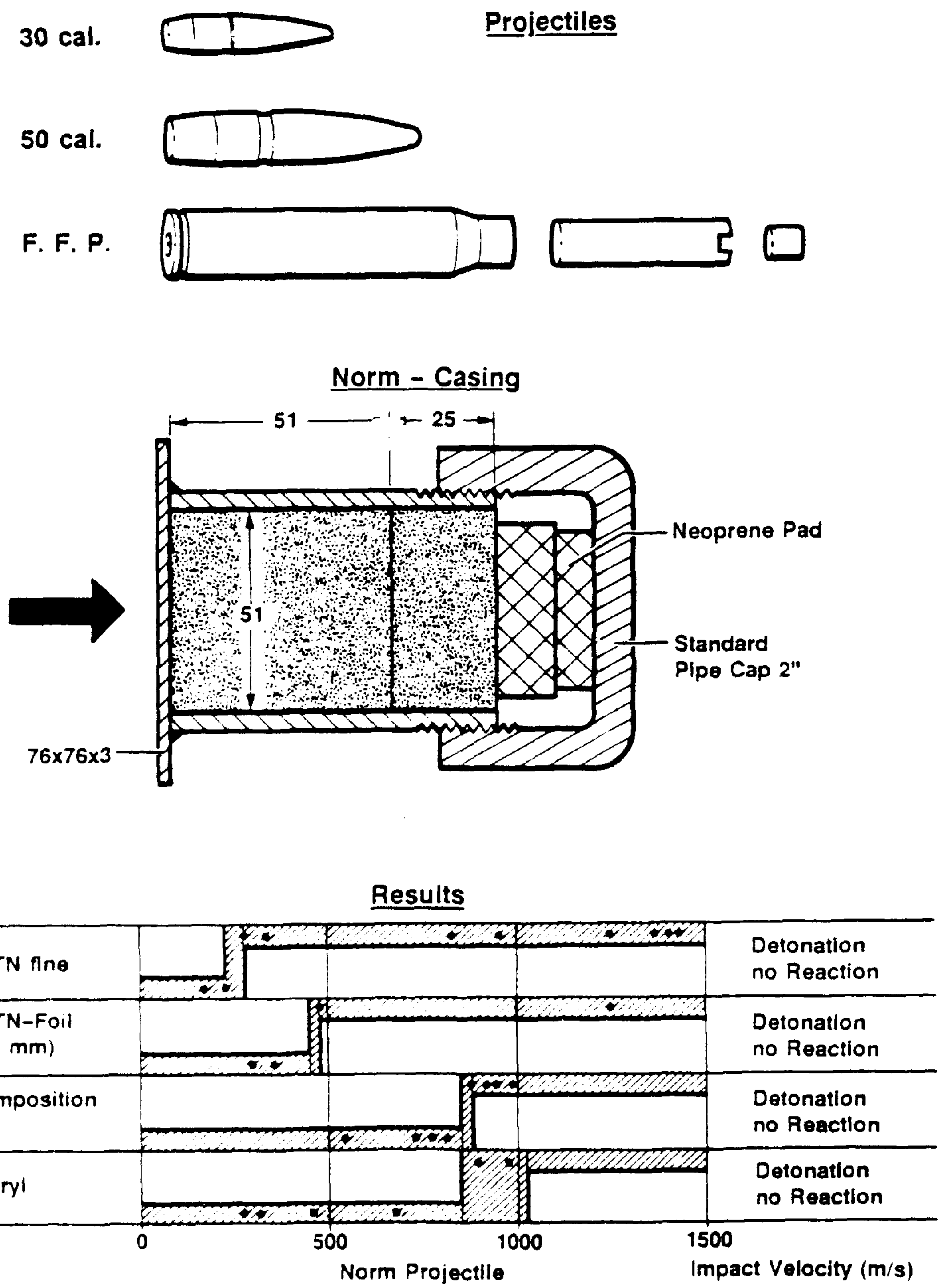
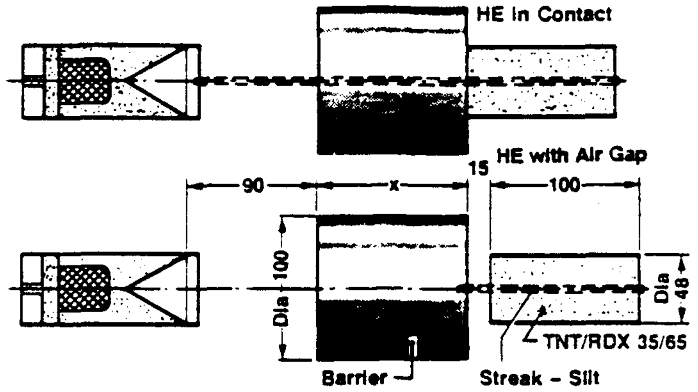


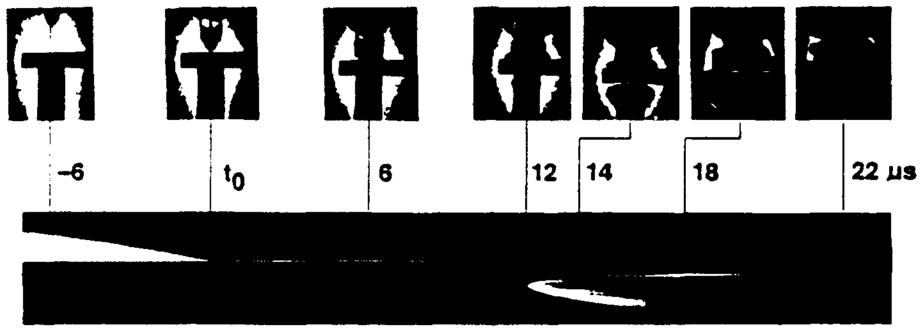
Figure 15

Instrumented Shaped Charge Test

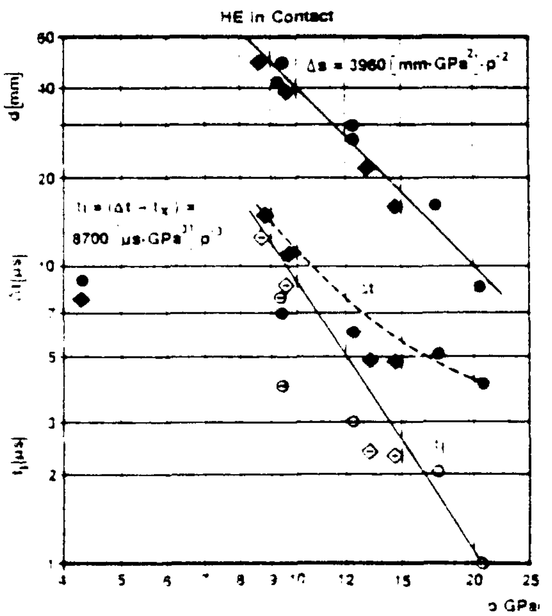
Test Set - ups



Framings & Streak



Test Results



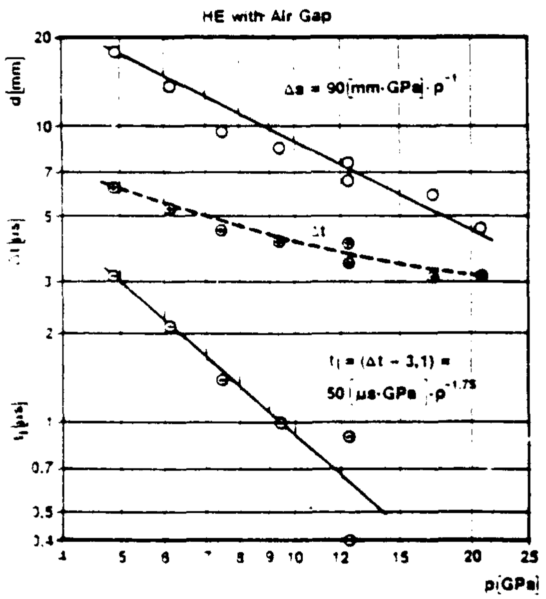


Figure 16

Temperature Tests

Test	Probe	Reaction		Result
		Mode	Type	
DTA/TGA/DSC	P/(C)	Ha	R	T
Self Ignition	P	Ha	R	T
Unc. Burning [*1]	P	Ha	LR	t; No Det.
Cook-Off [*2]	C	Su	R/LR	t=f(T); Fragm.
Fuel Fire	C/WH	Su	LR	t, Fragm.
Fragm. Pincer	C	Su	R/LR	c·m·T

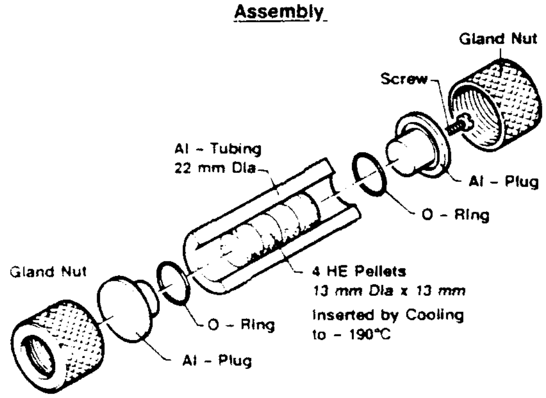
[*1] or Ignition
or Small Scale Burning Test
or Stahlhülsentest

[*2] or One Dimensional Time to Explosion Test (ODTX)
or Small Scale Burning Tube Test
or Time to Explosion Test

Figure 17

ODTX

Assembly



Test System

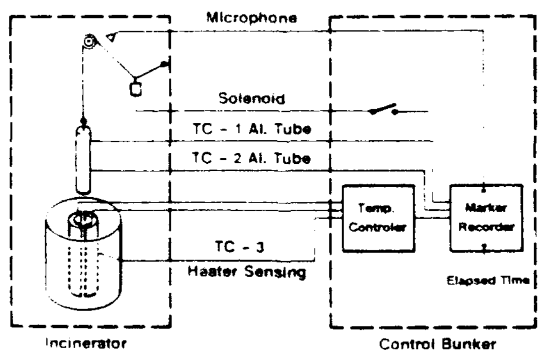
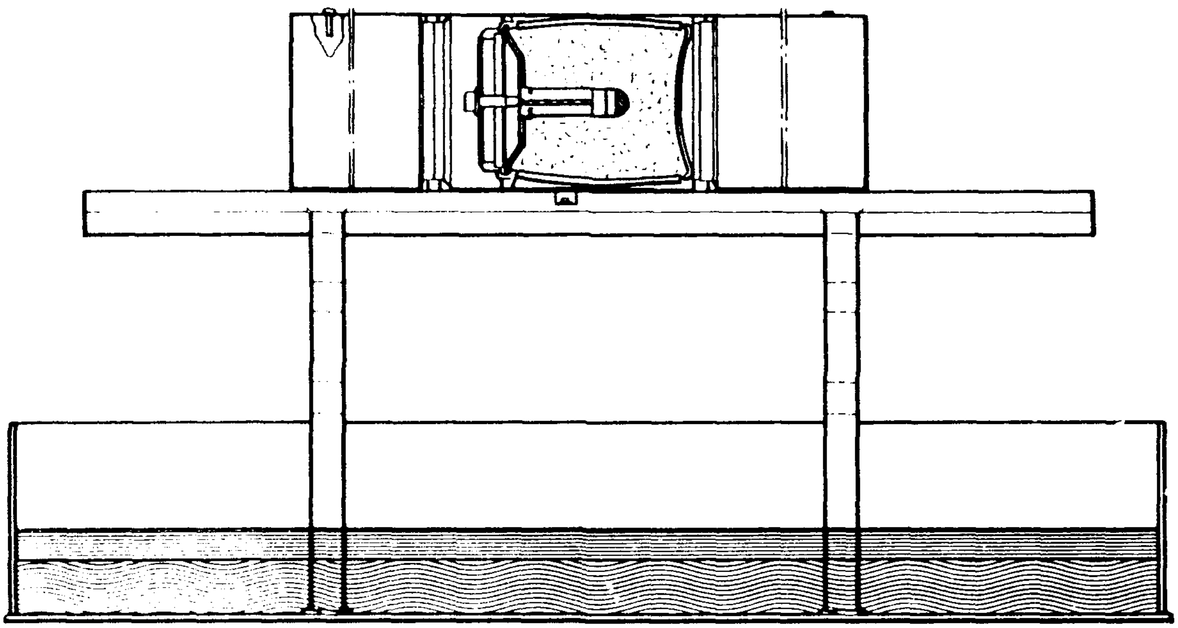


Figure 18

Fuel Fire Test

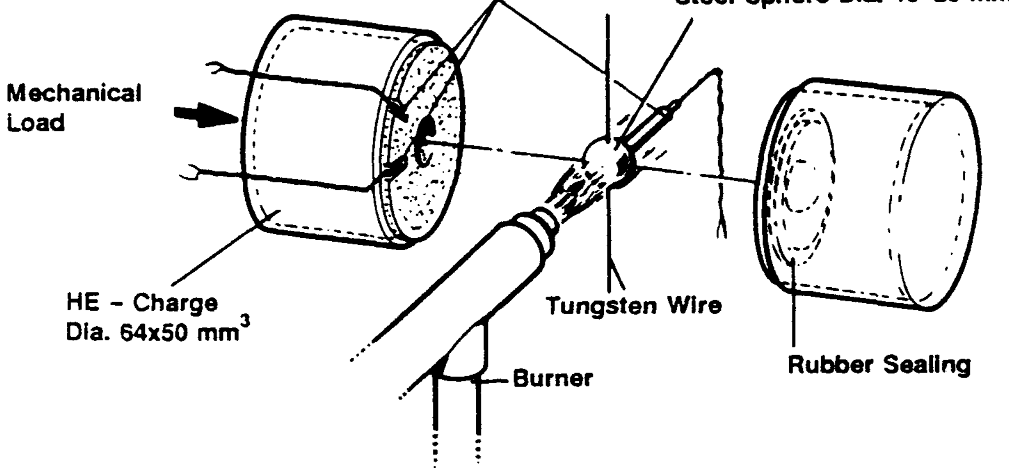


1500 x 1000

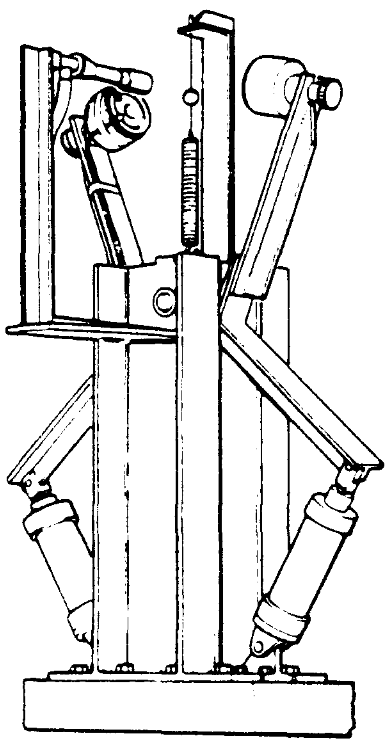
Figure 19

Fragment Pincer Test

Heating up



Test Set - up



Results

TNT/RDX/WAX 49/50/1, Steel Sphere 20 mm Dia, Mechanical Load 2000,"Sealed"

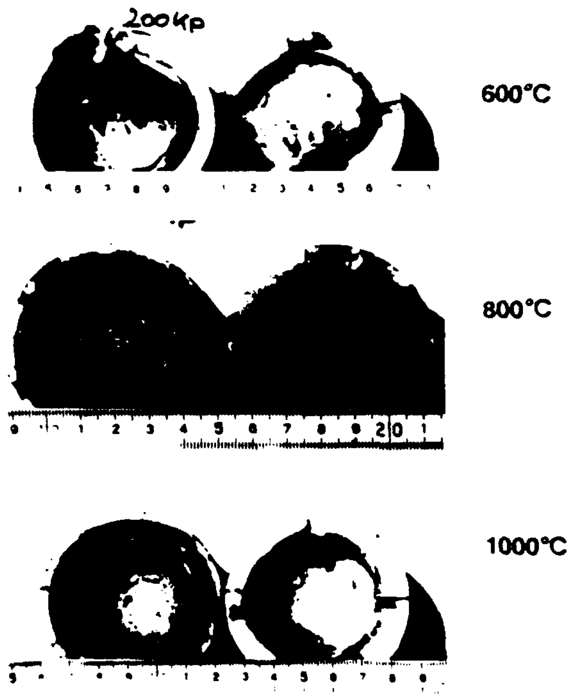


Figure 20

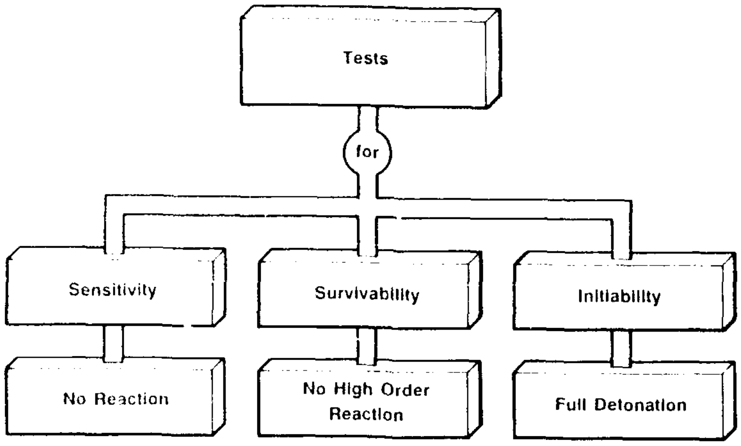


Figure 21

MIL-STD-2105 A (NAVY)
19.Jan. 1990

NOTE: This draft, dated 19 January 1990, prepared by the Naval Sea Systems Command (OS), has not been approved and is subject to modification. DO NOT USE PRIOR TO APPROVAL. (Project SAFT-0024)

INCH-POUND
MIL-STD-2105A (NAVY)

SUPERSEDING
DOD-STD-2105 (NAVY)
9 September 1982

MILITARY STANDARD

HAZARD ASSESSMENT TESTS FOR NON-NUCLEAR MUNITIONS

AMSC

AREA SAFT

DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.

Figure 22

MIL-STD-2105A (NAVY)

Explosive reaction levels.

a. **Detonation Reaction (Type I).** The most violent type of explosive event. A supersonic decomposition reaction propagates through the energetic material to produce an intense shock in the surrounding medium, e.g., air or water, and very rapid plastic deformation of metallic cases. followed by extensive fragmentation. All energetic material will be consumed. The effects will include large ground craters for munitions on or close to the ground, holing/plastic flow damage/fragmentation of adjacent metal plates and blast overpressure damage to nearby structures.

b. **Partial Detonation Reaction (Type II).** The second most violent type of explosive ever . Some, but not all of the energetic material reacts as in a detonation. An intense shock is formed; some of the case is broken into small fragments; a ground crater can be produced, adjacent metal plates can be damaged as in a detonation, and there will be blast overpessure damage to nearby structures. A partial detonation can also produce large case fragments as in a violent pressure rupture (brittle fracture). The amount of damage, relative to a full detonation, depends on the portion of material that detonates.

c. **Explosion Reaction (Type III).** The third most violent type of explosive event. Ignition and rapid burning of the confined energetic material builds up high local pressures leading to violent pressure rupturing of the confining structure. Metal cases arc fragmented (brittle fracture) into large pieces that are often thrown long distances. Unreacted and/or burning energetic material is also thrown about. Fire and smoke hazards will exist. Air shock are produced that can cause damage to nearby structures. The blast and high velocity fragments can cause minor ground craters and damage (break-up, tearing, gouging) to adjacent metal plates. Blast pressures are lower than for a detonation.

d. **Deflagration Reaction (Type IV).** The fourth most violent type of explosive event. Ignition and burning of the confined energetic materials leads to nonviolent pressure release as a result of a low strength case or venting through case closures (leading port/fuze wells, etc.). The case might rupture but does not fragment; closure covers might be expelled, and unburned or burning energetic material might be thrown about and spread the fire. Pressure venting can propel an unsecured test item, causing an additional hazard. No blast or significant fragmentation damage to the surroundings; only heat and smoke damage from the burning energetic material.

e. **Burning Reaction (Type V).** The least violent type of explosive event. The energetic material ignites and burns, non-propulsively. The case may open, melt or weaken sufficiently to rupture nonviolently, allowing mild release of combustion gases. Debris stays mainly within the area of the fire. This debris is not expected to cause fatal wounds to personnel or be a hazardous fragment beyond 50 feet.

f. **Propulsion (Type VI).** A reaction whereby adequate force is produced to impart flight to the test item in its least restrained configuration as determined by the life cycle analysis.

Figure 23

Explosive Reaction Levels

MIL-STD-2105A (NAVY)

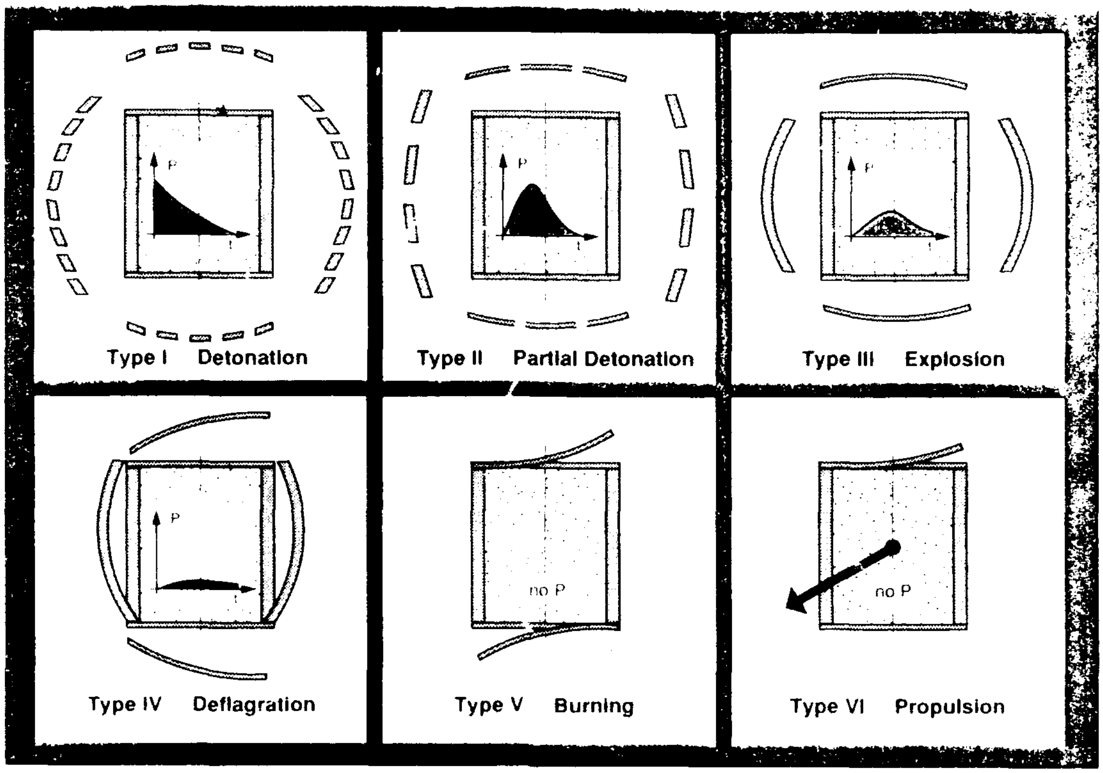


Figure 24

RATTAM Tests UK

Concern by the Royal Navy about the safety of explosive munitions mounted or stored in ships, particularly guided weapon warheads, led in the UK to an assessment programme generally known by the acronym RATTAM (Response to ATTack on AMmunition). The aim of the programme was to obtain the necessary data to advise the RN on the risk to RN ships carrying particular weapons, if those weapons were subject to terrorist attack.

It was decided to use the following weapons for the tests; they are readily available in UK service and are typical of what a terrorist might obtain:

Code	Weapon
A (i)	7.62mm AP
A (ii)	0.50 in AP
B	20mm HE
C	84mm HEAT

The weapons were fired a explosive munitions protected by a 6mm mild steel plate representing the ships side; in some tests the protective plate was not used. The 0.5 in AP has been used most in the tests.

Figure 25

Response Categories (RATTAM - UK)

Six categories of response were decided upon for the munitions under test:

(I) No response

(II) Burning - the explosive filling ignites and burns, The munition case may open up but the munition is not moved propulsively.

(III) Deflagration - The explosive store is ignited leading to rupture and often accompanied by the ejection of unreacted or burning explosive

(IV) Mild Explosion - The explosive store is ignited leading to violent rupture. Unreacted or burning explosive may be ejected. Major pieces of the store may be thrown a considerable distance.

(V) Severe Explosion - The explosive store is blown apart with considerable violence. The damage from blast and fragmentation is extensive but less than that associated with detonation, Large fragments are ejected accompanied by unreacted or burning explosive.

(VI) Detonation

Figure 26

Item Number and Test Sequence

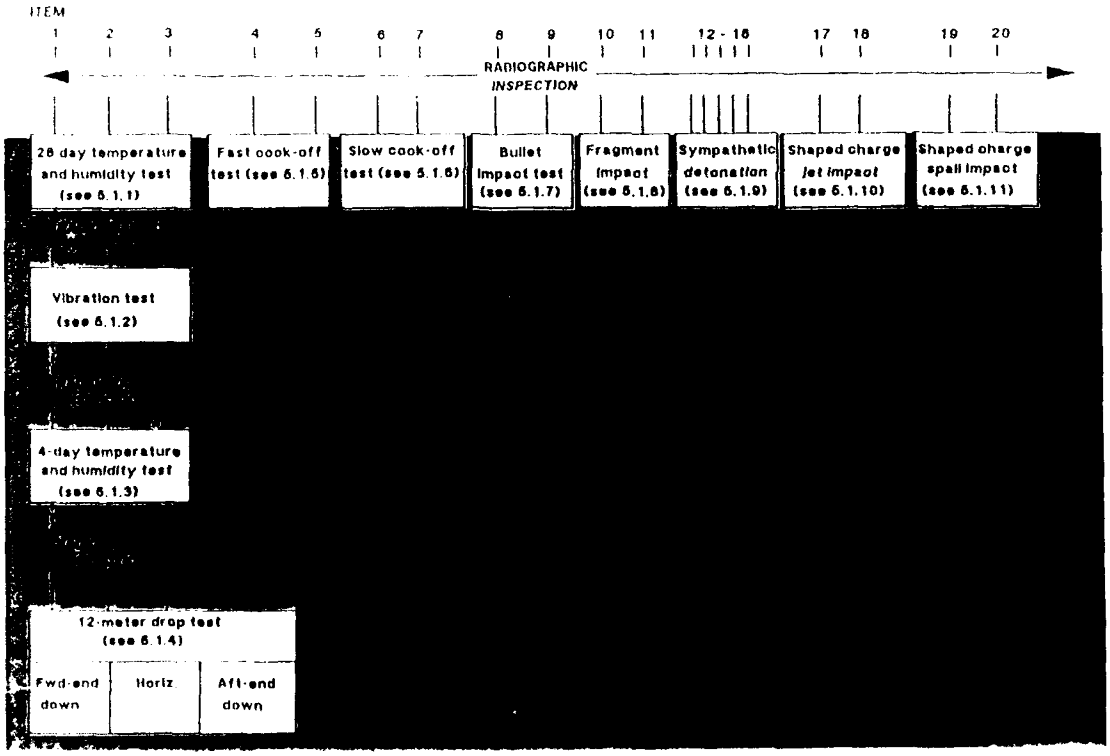


Figure 27

Fast Cook-off Test
5.1.5 MIL-STD-2105A (NAVY)

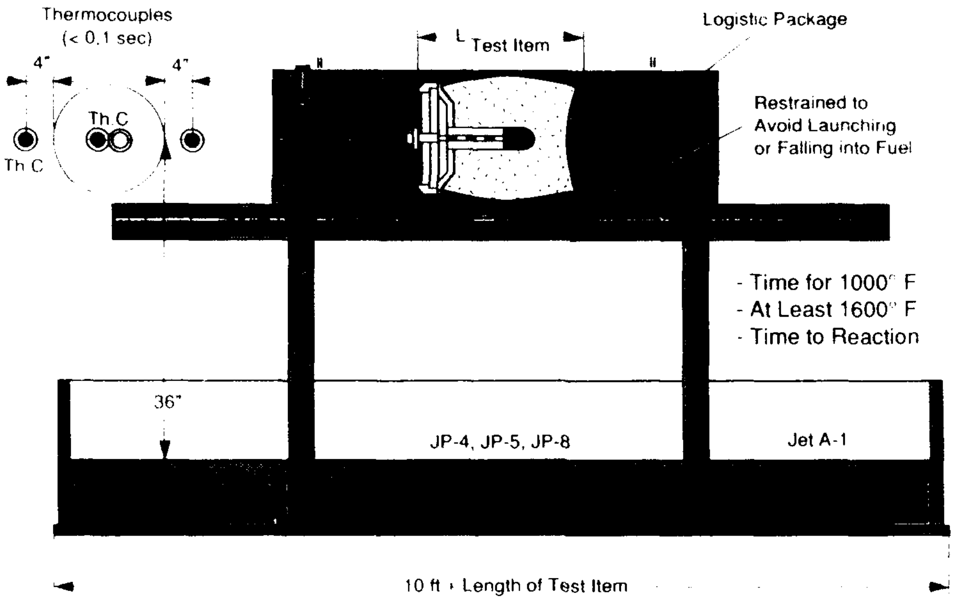


Figure 28

Slow Cook-off Test
5.1.6 MIL-STD-2105A (NAVY)

6° F per Hour = 3,3°C / h

Start at 100° F = 37,8°C Below Predicted

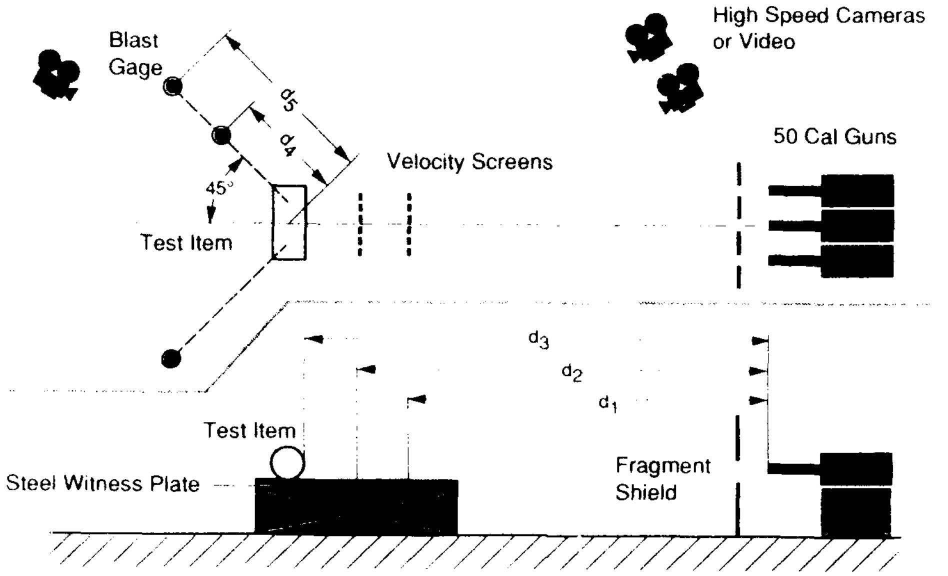
Reaction Temperature

Continnously Measurement of Temperature

Figure 29

Bullet Impact Test

5.1.7 MIL-STD-2105A (NAVY)



Notes.

d_1 = Distance to First Velocity Screen
d_2 = Distance to Second Velocity Screen } v_p ± 50 ft/sec

d_3 = Distance to Test Item
d_4 = Distance to First Blast Gage
d_5 = Distance to Second Blast Gage(s)

Figure 30

Fragment Impact Test

5.1.8 MIL-STD-2105A (NAVY)

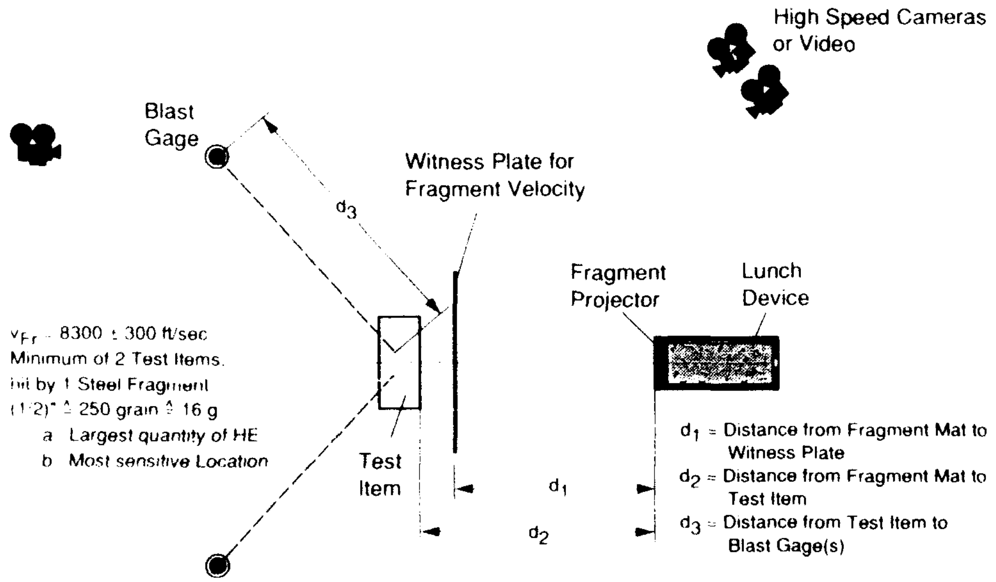


Figure 31

Sympathetic Detonation Test

5.1.9 MIL-STD-2105A (NAVY)

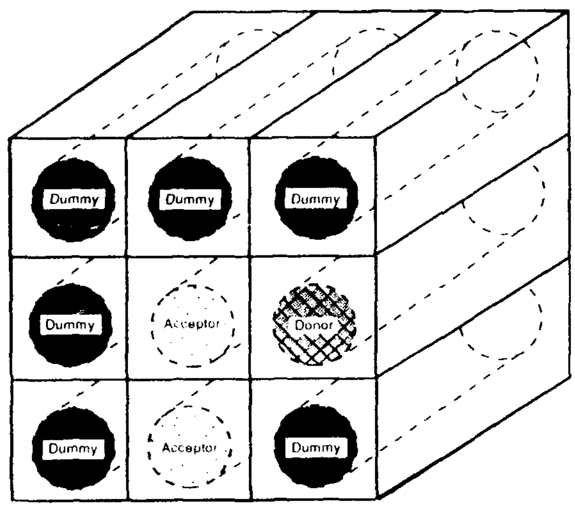
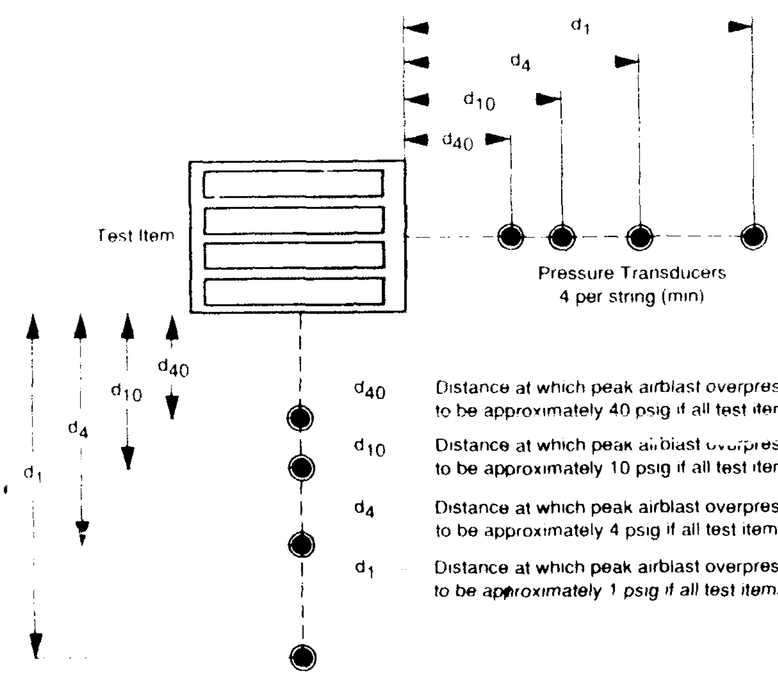


Figure 32

Sympathetic Detonation Test

Placement of Pressure Gages



d_{40} Distance at which peak airblast overpressure is expected to be approximately 40 psig if all test items detonate

d_{10} Distance at which peak airblast overpressure is expected to be approximately 10 psig if all test items detonate

d_4 Distance at which peak airblast overpressure is expected to be approximately 4 psig if all test items detonate

d_1 Distance at which peak airblast overpressure is expected to be approximately 1 psig if all test items detonate

Figure 33

Shaped Charge Impact Test

5.1.10 MIL-STD-2105A (NAVY)

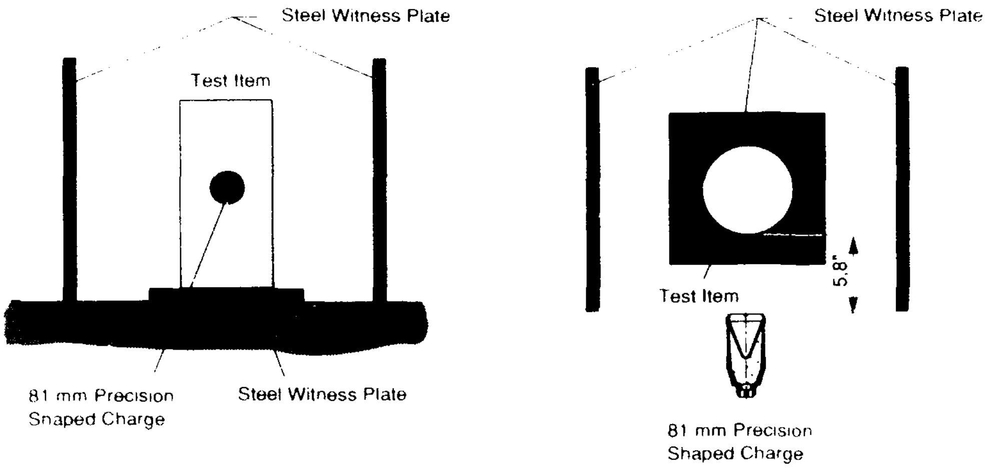


Figure 34

Shaped Charge Jet Impact Test

5.1.10.3.2 MIL-STD-2105A (NAVY)

The M 42/M46 grenade shall be configured as follows:

Explosive fill:	**30 grams of Composition A-5 conforming to MIL-E-14970**		
Cone angle:	**Trumpet with 3" radius**		
Dimensions:	**Height of cone**	=	**1.3 inches**
	Outside diameter	=	**1.315 inches**
	Inside diameter	=	**1.237 inches**
	Wall thickness	=	**0.075 inches**
Liner description:	**Copper strip, cold-rolled, soft annealed, conforming to QQ-C-576**		
	Electrolytic tough pitch		
	Grain size < ASTM grain size 8		
	Non-earring quality with suppressed cube texture		
Body:	**M 42/M46 body load assembly (without fuze)**		

Figure 35

Grenade M 42 / M 46

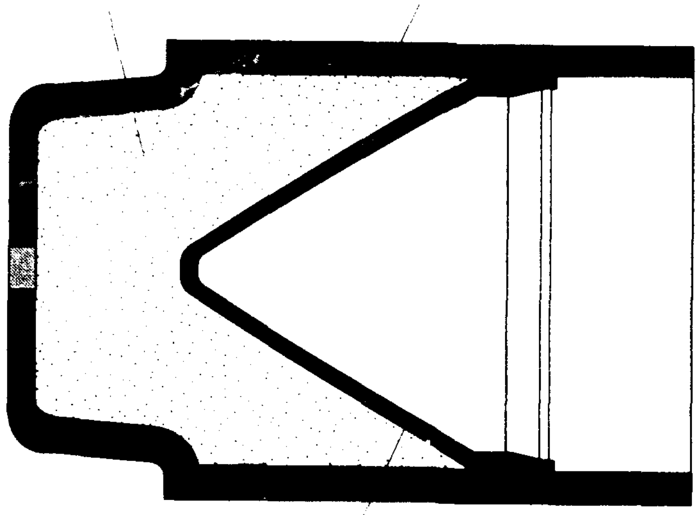


Figure 36

Shaped Charge Jet Impact Test

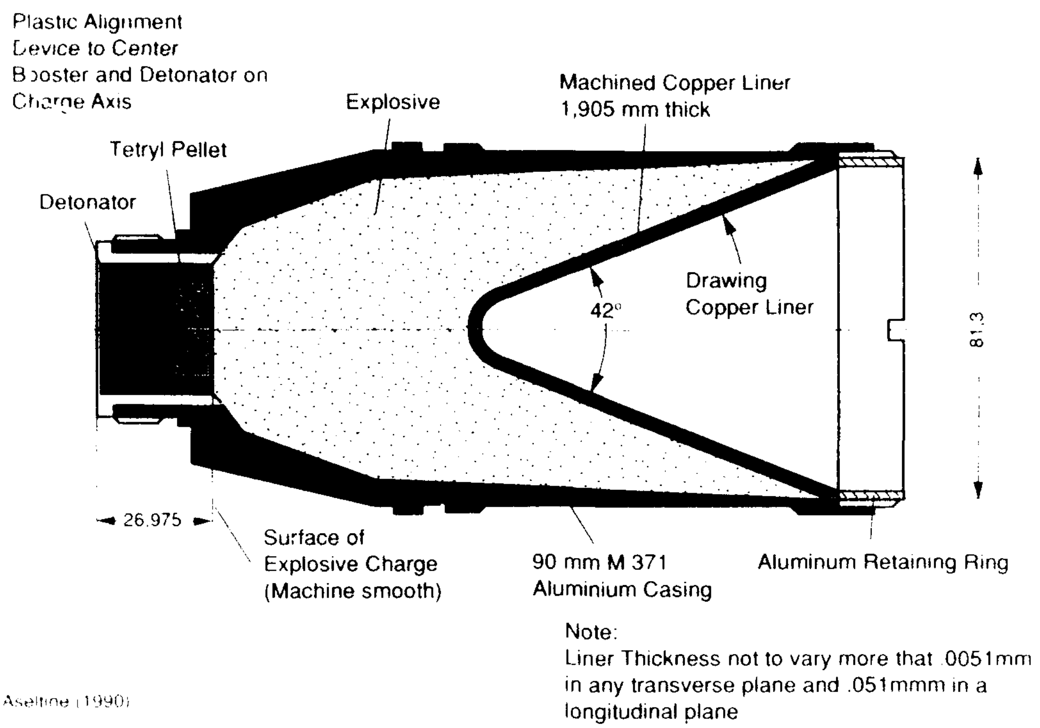
5.1.10 MIL-STD-2105A (NAVY)

The 81 mm precision shaped charge shall be configured as follows:

Explosive fill:	1,8 pounds of Composition B conforming to MIL-C-401	
Cone angle:	42	
Dimensions:	Height of cone	= 3.7 inches
	Outside diameter	= 3.2 inches
	Inside diameter	= 2.91 inches
	Wall thickness	= 0.075 inches
Liner description:	Oxygen-free copper conforming to ASTM B152 with a temper of OS025 Grain size < 50 microns after stress relief No shear forming Depp drawn anneal	
Body:	Standard 90-mm M371E1 recoilles rifle round	

Figure 37

Standard Shaped Charge



Aseltine (1990)

Figure 38

Spall Impact Test

5.1.11 MIL-STD-2105A (NAVY)

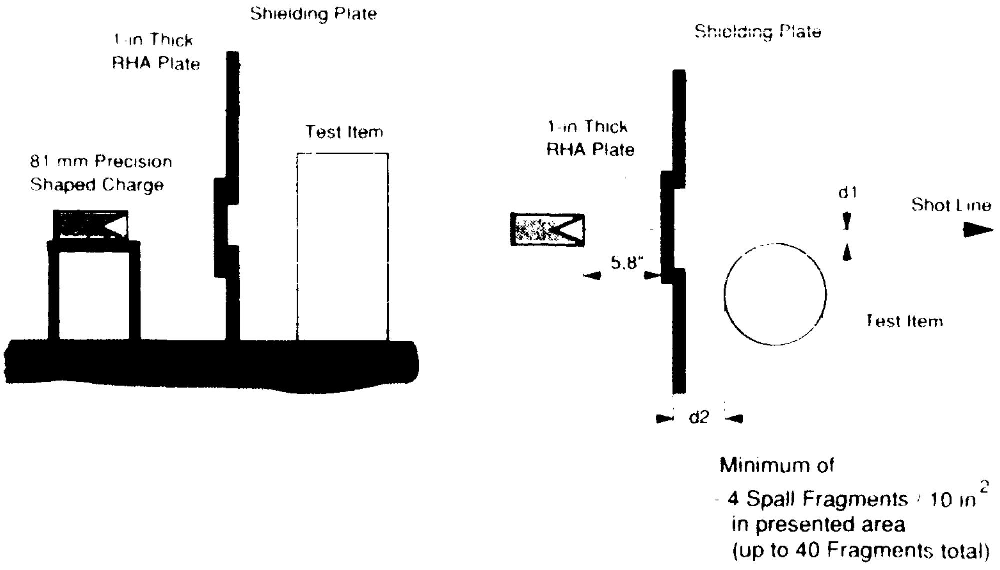


Figure 39

Discussion

QUESTION BY ?, GERMANY: What do you think about the value of shape charge testing in the field of insensitive munitions?

ANSWER: The threat comes from shape charge warheads attacking our tanks, therefore we want insensitive or low sensitivity munitions in our tanks that will have no reaction or mild reaction to shape charge attack.

METHODOLOGIE DE CONCEPTION DE CHARGES MILITAIRES A IMMUNITE RENFORCEE

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J. FERRON

Développement Charges Militaires

THOMSON BRANDT ARMEMENTS

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France

SOMMAIRE

La conception de charges à immunité renforcée demande une participation active entre le concepteur de la charge et le formulateur , afin d'optimiser les définitions qui répondent aux spécifications opérationnelles

Cette méthodologie a été établie en exploitant les résultats des immunités acquises depuis 20 ans par T B A sur les études et développements de charges de missiles et de munitions aéroportées

Des exemples associant T B A (concepteur de charges) et S N P E (formulateur et fournisseur de compositions explosives) illustrent l'application de cette méthodologie à l'étude de charges de missiles air air et sol air ainsi qu'aux munitions aéroportées à forts confinement

LISTE DES SYMBOLES

T B A Thomson Brandt Armements

S N P E Société Nationale des Poudres et Explosifs

DGA / S T P E Direction Générale de l'Armement / Service Technique des Poudres et Explosifs

DGA / S T E T Direction Générale de l'Armement / Service Technique des Engins Tactiques

DGA / D R E T Direction Generale de l'Armement / Direction des Recherches et Etudes Techniques

DGA / DCN / STCAN Direction Générale de l'Armement /Direction des Constructions Navales / Service Techniques des Constructions et Armes Navales

1. INTRODUCTION

L'immunité des munitions aux environnements accidentels est un souci permanent du concepteur de charges militaires afin de garantir la sécurité d'emploi et la fiabilité d'exécutions des missions opérationnelles De nombreux exemples souvent tragiques ont démontré la nécessité impérative de développer des munitions à risques atténués.

Les études financées en France par les organismes de tutelle tels que le S T P E le S T E T et la D R E T ont permis la mise au point de formulations explosives de moins en moins sensibles et l'étude de l'optimisation des structures des charges pour ces formulations afin d'assurer la conformité aux spécifications de besoin

La présente communication effectue la synthèse des résultats des développements TBA (Concepteur de charges) conduits en association avec SNPE (Formulateur et fournisseur de compositions explosives) , en présentant

-les résultats des immunités acquises dans divers configurations struturales avec les differents explosifs disponibles à l'époque des développements,

-le logigramme de conception des charges à immunité renforcée afin de satisfaire aux spécifications actuelles d'immunité

2 SPECIFICATIONS ACTUELLES D'IMMUNITE

Les immunités specifiées dans les nouveaux programmes de développement des charges de missiles et des munitions aéroportées

destinées à l'Armee de l'Air ou la Marine sont récapitulées dans le tableau 1 ci après.

EPREUVES	EVENEMENT A CONSTATER	DOCUMENTS A UTILISER			
		USA	UK	F	STANAG
[illegible]	PASDEREACTION [illegible] SEVERE QUE [illegible]	[illegible]-STD-2105A PROJET [illegible]	[illegible] OBP 4224[illegible] [illegible]	[illegible] N° 9252-1 [illegible]	[illegible]
[illegible]	[illegible]DEREACTION [illegible]	[illegible] PROJET [illegible]	....	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	....
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		[illegible]	

TABLEAU 1

3. ANALYSE DES RESULTATS D'IMMUNITE ACQUISE DEPUIS 25 ANS PAR TBA

3.1 Chargements en hexogène tolite .

Les résultats des épreuves d'immunites (cf tableau 2) appliquées aux charges de missiles air/air et air/sol développées dans les années 1960/1970 en utilisant des chargements principaux en hexogène / tolite armaturés de fibres de verre mettent en evidence l'importance de l'influence de la structure et de l'interface structure / chargement sur

l'acquisition de l'immunité à l'impact par balle la présence d'une protection thermique en silicone interposée entre la structure en acier et le chargement principal confère aux charges l'immunite à la balle perforante de 12,7mm

3.2 Chargements composites à liants inertes

Le développement d'explosifs à liants inertes dans les années 1970 chez SNPE a permis l'emploi de chargements de sensibilités réduites par rapport à l'hexogene / tolite. Ces chargements présentent en outre de très bonnes caractéristiques thermomécaniques dans les plages des temperatures d'emploi des missiles développes à cette epoque (-54 °C , +90°C)

Les epreuves d'immunité aux environnements accidentels appliquées à la première charge à éclats à gerbe divergente (cf tableau 3) équipée d'un chargement en hexogène /liant plybutadiène ont mis en évidence les comportements suivants du chargement agressé dans une structure assurant le "deconfinement " des produits de décomposition :

-Epreuve incendie type feu de kérozène

-arrêt de la réaction de décomposition dès l'instant où l'ouverture de la stucture assure la mise à l'air libre du chargement ,

-non transition décomposition /deflagration / détonation

-Impact de balle et obus.

-réaction limitee à une combustion en cas d'impact d'obus de 20 mm , ou de balle de 7,62mm.

-Détonation par influence

-non détonation dans les conditions de stockage de la charge expérimentee

Ces résultats ont été confirmés et complétés lors du développement

-soit de nouvelles charges de missiles à gerbes " focalisées"(gerbes étroites à bords quasi parallèles) utilisant le même type d'explosif et des structures assurant le déconfinement des produits de décomposition (cf tableau 3) Lors de l'application de ces épreuves nous avons observé

-une réaction limitée à la combustion en cas d'impact de balle perforante de 12,7 mm

CHARGEMENTS EN HEXOGENE / TOLITE

RESULTATS D'EPREUVES D'IMMUNITE A L' IMPACT DE BALLE DE 12,7 MM

A LA VITESSE D'IMPACT DE 850 M/S

EQUIPEMENTS	INTERFACE CHARGEMENT CORPS DE CHARGE	TYPE DE BALLE	RESULTATS
CHARGE DE [illegible]	CHARGEMENT EXPLOSIF ISOLE PAR UNE ENVELOPPE DE PROTECTION THERMIQUE	PERFORANTE	ABSENCE DE REACTION
		TRACANTE	COMBUSTION
[illegible]	CHARGEMENT AU CONTACT AVEC LA PAROI DE MAQUETTE	PERFORANTE	DETONATION

[illegible] de paroi des deux types d'equipement sont comparables

TABLEAU 2

CHARGEMENTS COMPOSITES A LIANTS INERTES

RESULTATS D'IMMUNITE AUX EPREUVES D'ENVIRONNEMENT ACCIDENTELS

EQUIPEMENTS	PARTICULARITES DE DEFINITION	EPREUVES	RESULTATS
[illegible]	[illegible]	[illegible]	[illegible] CHARGEMENT APRES [illegible]
		[illegible]	[illegible]
		[illegible]	
		[illegible]	[illegible]
		[illegible]	[illegible]
		[illegible]	[illegible]
		[illegible]	[illegible]
		[illegible]	[illegible]
		[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible] CHARGEMENT [illegible]

TABLEAU 3

le déconfinement de la charge et la combustion du chargement en environnement feu de kérosène ",

- la non détonation par influence dans les conditions d'emploi opérationnel en tubes lanceurs (tube lanceur en fibre de verre de faible épaisseur) .

-soit de charges perforantes de munitions anti pistes présentant un très fort confinement (corps de forte épaisseur) et équipées d'un dispositif axial de déconfinement . La connaissance du comportement de ce type de munition est actuellement limitée à celle du comportement en incendie feu de kérosène" : déconfinement du corps de charge et combustion du chargement . Des études de comportement en non détonation par influence et impact de balle sont en cours

3.3 Conclusions de l'analyse TBA

Les immunités spécifiées peuvent être acquises en associant dès le début du développement le formulateur et le concepteur de charge , afin de sélectionner les formulations qui présentent les meilleures performances par rapport aux efficacités imposées par les spécifications de besoin et qui offriront les meilleurs garanties d'immunité . Les quatre facteurs les plus importants qu' il faut associer lors de la définition de la munition sont

-emploi d'un explosif à forte pression d'initiation (cf tableau 4) ,

-structure de charge équipée d un dispositif de déconfinement ,

-interposition si nécessaire de matériaux atténuateur de choc à l'interface chargement / corps de charge ou à l'extérieur de la charge ,

-emploi de composition présentant de bonnes caractéristiques thermomécaniques garantissant un bon comportement à l'impact de balle

TYPE D'EXPLOSIF	REPERE	PRESSION D'INITIATION (Kb)
[illegible]	A	
[illegible]	B	ENVIRON [illegible]
[illegible]	C	ENVIRON [illegible]
[illegible]	D	[illegible]
[illegible]	E	[illegible]

TABLEAU 4

4 LOGIGRAMME DE CONCEPTION DES CHARGES A IMMUNITE RENFORCEE

Le logigramme d'étude de charge à immunité renforcée aux environnements accidentels est représenté sur la figure [illegible] Sur ce logigramme apparait clairement les activités coordonnées du formulateur et du concepteur

5 EXEMPLES APPLICATION DU LOGIGRAMME

Les développements des munitions citées dans le paragraphe 3 ont conduit à la conception de munitions à immunité renforcée qui utilisent des chargements principaux et des relais d'amorçage réalisés en explosifs dont la pression d'initiation est voisine de [illegible] Kbar

Ces munitions sont

-une charge air air anti aéronefs (explosif C) ,

-une charge sol / air anti missile et anti aéronefs (explosif C) ,

-une bombe perforante anti pistes (explosif E)

Ces exemples de réalisation démontre que l'acquisition de l'immunité aux environement accidentels ne se traduit pas inéluctablement par une réduction de performance si l'immunité est prise en compte dès le début du développement . Dans certaine mission ,antipiste par exemple l' étude de renforcement de l'immunité a conduit à une amélioration de performance

LOGIGRAMME DE CONCEPTION

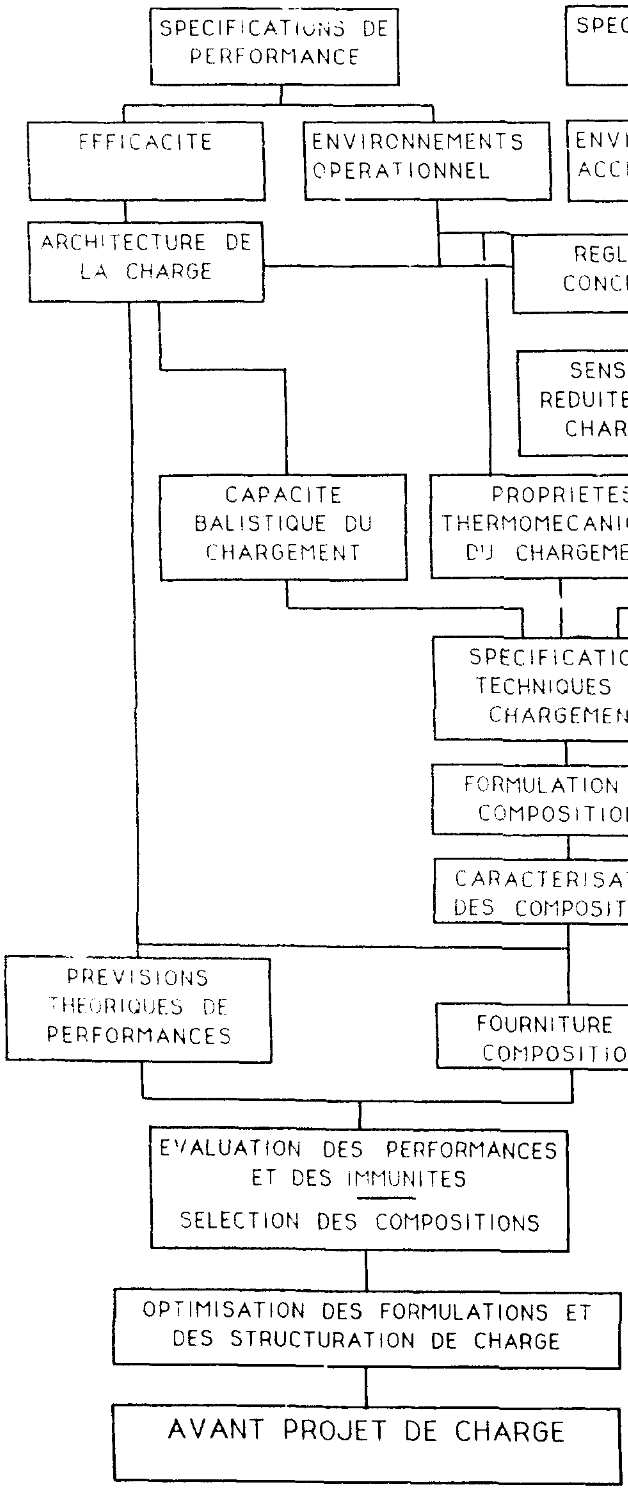

Figure 1

"LESS SENSITIVE EXPLOSIVES"

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INTRODUCTION

Explosives are the active constituents in ammunition. Their high energy output per unit of time is used for propulsion and terminal ballistic action. This capability is also a continuous threat to the user and the civilian surroundings due to the possibility of unwanted reactions.
The vulnerability of ammunition to heat (eg. fuel fire), bullet/fragment impact and sympathetic detonation was recognised as a high priority problem to be solved; especially for the battlefield situation it was proven by operation research studies that introduction of Insensitive Munitions (IM) is of vital importance to survive.
To improve the existing munitions, the munitions must be considered as a total concept. Propellants explosives and pyrotechnics must be of a less sensitive nature, in the case of accidental reactions the munition is capable of venting the overpressure quickly by venting holes. This can be integrated in the munition design (grenade, booster cup, rocket motor).
This study deals with the search for less sensitive high explosives.
For practical reasons it was decided to make use of existing explosives; the "desensitising" action is established by the addition of a (commercial available) polymer binder (plastic binder, PBX = Plastic Bonded eXplosive). This report describes the research done in this field. The first part of the research concentrated on the influence of the binder on the PBX system, the second part was devoted to the influence of the explosives manufacturing process, particle size and particle shape.

Plastic Bonded Explosives

A plastic bonded explosive is composed of an energetic high explosive like RDX (hexogen) or HMX (octogen) and a polymer binder. The function of the binder is to protect the explosive crystals from quick initiation due to outer stimuli. This is realised by coating the entire crystal surfaces of the explosive by a thin polymer layer (1). This layer can absorb the accidental energy pulses and distribute them evenly over the volume of the PBX, thereby preventing local decomposition and initiation. Another important function of the binder is its high mechanical strength: the binder will create a void free matrix between the explosive particles. The so formed PBX has a high mechanical strength that prevent crack formation even under high pressure conditions. This is very important in the prevention of DDT (Deflagration to Detonation Transition) as this phenomenon is stimulated by cracks and voids in the explosive.

PBX composition

Pre-polymer Hardener

The binder we have chosen consists of HTPB (Hydroxy Terminated Poly-ButaDiene). The reason for this choice was the excellent, well-described mechanical properties of this binder; HTPB is used in reasonable quantities in the rocket motor industry. HTPB consists of (50 molecules) chains of butadiene which are able to form a network by their functional (OH = Hydroxy) end groups. This reaction proceeds by the addition of isocyanates like TDI (Toluene Di Isocyanate). For this study we used isophorodiisocyanate (IDPI) because it is less volatile. The functional NCO group of the Isocyanate reacts with the OH group of the HTPB. Depending on the OH/NCO ratio it is possible to control the number of cross-links between the polybutadien chains. A low number of cross links results in a sticky (a lot of reactive groups are still present), deformable product, which cannot be used in ammunition. A high cross-link density (nearly all the reactive groups have reacted) results in a very hard, brittle product. The optimum cross link density will be between those extremes.

Anti-oxidant

The poly butadiene chain has an unsaturated C C bond, which can react with oxygen (stimulated by light). TNO has studied the influence of aging on PBX, and the effect of the addition of anti oxidants to improve the shelf-life. It was proven that anti oxidants like DTBHQ (2,5 Di Tertiair Butyl Hydro Quinone) and Flexzone (N phenyl N cyclohexyl p phnylene diamine) improves the aging behaviour of binders in PBX.

Bonding Agent

The interaction between the explosive and the binder has always be a problem because of the fact that explosives are more polar in nature where the binder has more the characteristics from non polar molecules. This can be solved by the use of bonding agents; a bonding agent is a molecule with a polar side that can interact with the explosive surface, and a non polar side that has a better affinity to the binder system. The bonding agent, with proven qualities in PBX formulations, we have chosen for this study is Dantocol.

Plasticizer

The mechanical properties of a plastic binder can strongly be influenced by the use of a plasticizer. Due to its physical and chemical properties it can be situated between the long polymer chains and in this way it can act as a kind of lubricant. If the plasticizer is too volatile it can exudate from the binder matrix this makes the movement of the long polymer chains more difficult, resulting in chain rupture and consequent crack formation. As a plasticizer we used isodecylpelargonaat (IDP).

Wetting Agent

This is a processing aid: the problem is to distribute 85 % of a solid loading over a viscous liquid. The wetting agent acts like a soap; in this way the solid explosive is moistened more quickly and the overall viscosity of the mixture is lowered so we still have a castable mixture. In this study we used Lecithine as a wetting agent.

Explosive

The important features of the explosive are:
1. Well available 2. High density 3. High melting/decomposition temperature. Most promising explosives that fulfil this demands are the nitramines HMX and RDX. In order to achieve a solid loading of 85 % and more it is necessary to make use of bimodal and multimodal particle size distributions. The explosive crystals must be void free and of a regular shape, for practical reasons we started with industrial grade explosives from Dyno (No).

PART I The influence of the binder

The influence of the binder was studied by varying the HTPB/IDPI ratio (ref. 5, part II), in this way the cross-link density was varied between 0.7 and 1.0. As explosives we used RDX and HMX, the RDX originate from DYNO.

Detonation velocity and pressure were determined to check the performance of the explosive. The NOL Large Scale Gap Test was used to determine the shock sensitivity [3]. This method demands a large number of experiments and therefore another test was used to determine the "distance to detonation" and the "time to detonation". Normally the wedge test is used to determine these parameters, but we used a slightly different and simpler test method. With our test it is not possible to follow the acceleration of the shock wave during initiation.

Experimental

To reach a solid load of 85 wt% in the HMX and RDX with HTPB-based PBXes, attention must be paid to the particle size distribution of the explosive component. At the TNO-PML normally a bimodal mixture is used for the RDX-based PBXes and a trimodal mixture for the HMX based PBXes. The limits of the particle distributions and the percentages used in the bimodal and trimodal mixtures are given in Table 1. The two kinds of RDX were obtained from different sources; both contain about 6 wt% HMX.

Table 1 Particle size distribution of the explosives and the percentage used in the bimodal and trimodal mixtures.

Explosive	particle size (μm)	wt%
HMX	150 - 1400	53.3
	10 - 50	33.4
	100 - 500	13.3
RDX-I	200 - 500	66.0
	10 - 60	34.0
RDX-II	250 - 600	50.0
	10 - 50	50.0

Polyurethane was used as a binder in the PBXes. The binder composition is given in Table 2. The cross-link density was varied by changing the NCO/OH ratio between 0.7 and 1.0. The hydroxyl content of the HTPB was checked by standard methods involving acetylation.

Table 2 Composition of PBX (wt%).

Explosive	85.00
HTPB/IPDI	10.19
IDP	4.50
Lecithin	0.20
Dantocol	0.10
Flexzone	0.01

The PBXes were processed by mixing the components in a planetary Baker-Perkins mixer for about 6 hours under vacuum at 60 °C. Next they were cast under vacuum in teflon moulds and cured for 7 days at the same temperature. Cylinders of 50 mm in diameter and about 80 mm high were cast. Also "NOL"-tubes were filled to test the shock sensitivity of the explosives.

The detonation parameters to be determined were the detonation velocity and the detonation pressure. The first was measured with the help of ionization pins. The pressure was obtained indirectly by determining the pressure in a thin plexiglass (PMMA) plate in contact with the explosive. The piezo electric PMMA gives a polarization signal when a shock wave passes. The pressure in the PMMA was calculated from the time the shock wave required to travel through the plate. This technique (SIP = Shock Induced Polarization) is described extensively elsewhere (4). The detonation pressure can be calculated from the pressure in the PMMA if the Hugoniot of the reaction products is known.

The NOL Large-Scale Cap Test was used to determine the critical shock pressure at which 50 % of the experiments result in a detonation (3). Explosives were cast in steel tubes of i.d. = 37 mm, o.d. = 48 mm, l = 140 mm. Pressed tetryl (d = 50 mm, l = 50 mm) in combination with a PMMA attenuator was used as a donor.

A very simple test was used to obtain a measure for the distance to initiation and the time to initiation of the explosive (Fig. 1). In this test the same donor system was employed as for the NOL gap test, but now with a bare cylinder of explosive (d = 50 mm). With a streak camera the shock front in the PMMA was followed (back lighting). As soon as the shock wave enters the explosive, light is no longer detected by the camera. However, after an "initiation distance" (initiation time), a detonation wave with intensive light emission is generated. The light emission can be enhanced by attaching a piece of Sellotape to the explosive.

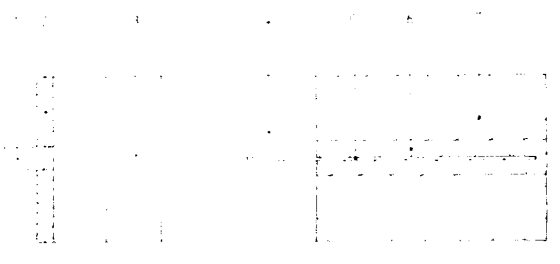

Figure 1 Test set-up to determine the distance to initiation and time to initiation. 1 detonator, 2 support plate, 3 tetryl, 4 PMMA, 5 streak slit, 6 Sellotape, 7 explosive.

Results

In Table 3 the results for the different PBXes are summarized.

Table 3 Detonation and shock sensitivity for the PBXes

Explosive	PRDX-I	PRDX-I	PRDX-II	PHMX	PHMX
Cross-link density	1.0	0.7	1.0	1.0	0.7
D (km/s)	7.9	8.0	7.9	8.2	8.1
P* (GPa)	19.5	19.5	20.0	23.0	22.4
P(50 %) (GPa)	3.2	3.2	3.7	3.0	3.0
Initiation distance (mm)	10.9	10.5	20.9	16.5	19.6
Initiation time (μs)	4.1	4.2	7.5	5.7	6.6

As might be expected, the detonation velocity (D) and pressure (P^*) do not vary for the different formulations. The detonation velocities (7.9 km/s for RDX-based and 8.2 for HMX-based) are very close to theoretically predicted values for PBXes with a solid load of 85 wt%. The pressures shown are the pressures in the thin plexiglass transducer.

Contrary to the invariability of the detonation parameters, the shock sensitivity is clearly influenced by variations in the PBX formulation.

The NOL gap test results (P(50 %)) for a series of explosives are given in Table 4. The sensitivities of the PBXes lie between those of RDX/wax (91/9) and pressed TNT at one extreme and CompB and cast TNT at the other. A great difference is found for the two RDX (I and II)-based formulations. As far as the NOL gap test results are concerned, the cross-link density does not have a significant influence on the shock sensitivity.

Also the measurements of the initiation distance and initiation time indicate that both RDX-based formulations differ considerably. However, the initiation distances obtained for the HMX-based formulations are longer than for PRDX-I, which is in contrast to the NOL gap test results. The results also show that with this test method the effect of different cross-link densities can be detected. A longer initiation distance is measured for the HMX-based formulations with a low cross-link density.

Table 4 Shock sensitivity for several explosives as determined by the NOL Large Scale Cap Test

Explosive	Density (kg/m^3)	Pressed/Cast	P (50 %) (GPa)
RDX	1610	P	1.0
RDX/wax (91/9)	1600	P	1.7
TNT	1580	P	2.0
PHMX	1640	C	3.0
PRDX-I	1580	C	3.2
PRDX-II	1580	C	3.7
TNT	1580	C	3.9
CompB	1710	C	4.4

Results burning tube tests and fragment attack test UK

RARDE Burning Tube Test UK

Description of test see NATO AOP 7 202-01-006

Description of Reaction Categories

Degree of Reaction	Reaction Description	Observation
0	fails to ignite	-
0/1	burning	end cap not ejected
1	pressure burst due to burning	end cap(s) ejected
2	deflagration	2 to 9 tube body fragments
3	explosion	10 to 100 tube body fragments
4	detonation	> 100 tube body fragments showing evidence of detonation

Results

Table 5 Burning Tube Test Results (Non Standard Conditions)

Composition	Data sheet ref	Test temp (C)	Igniter	Confinement	No. of tests	Distribution of results per reaction category 0	1	2	3	4	Avg. no of body frags
CPX 200/M6		amb	SR 886	std	2		2				1
CPX 200/M8		amb	ballistite	std	5	2	3				1
		amb	" "	55/clamp	3	3					1
		amb	" "	55/c/cavred	2	2					1
HU-23		amb	ballistite	std	2	1	1				1
		amb	ballistite	55 mm	2		2				1
		45	ballistite	55 mm	1	1					1
		47	SR 886	55 mm	2	2					1
		amb	ballistite	55 clamp	10	5	2	3			1.4
		amb	ballistite	55 c.cavred	2		1	1			2
		amb	ballistite	51 c/cavred	3		3				1
HU-24		amb	ballistite	std	2		2				1
		amb	ballistite	55 mm	2		2				1
		48	ballistite	55 mm	1	1					1
		48	SR 886	55 mm	2	2					1
		amb	ballistite	55 clamp	10		1	8	1		4
		amb	ballistite	55 c.cavred	2			2			7
		amb	ballistite	51 c cavred	2		2				1
[illegible]		amb	ballistite	std	10	8	2				1
		amb	ballistite	12.5mm wall	12	4	8				1
		amb	SR 44	std	3	1	2				1
		amb	ALI c	std	2	2					1
		amb	SR 44/ALI c	std	2		2				1
		amb	Al/MnO2	std	3	2	1				1
[illegible]		amb	ballistite	std	5				5		19
		amb		55 clamp	2				2		53
		40		std	3				1	2	91
[illegible]		amb	ballistite	55 clamp	5	3	1	1			1.4
		45	ballistite	55 clamp	5	2		3			1.4
[illegible]		amb	ballistite	55 clamp	7			4	3		4
		35	ballistite	55 clamp	5		1	2	2		1.9
[illegible]		amb	ballistite	std clamped	6	4	2				[illegible]
		45	ballistite	std clamped	2	[illegible]	1				1
[illegible]		amb	ballistite	std	8		4		1		[illegible]
		amb	SR 886	std	5	1	[illegible]				[illegible]
		amb	SR 44	55 mm	3		3				1
		amb	SR 886	55 mm	2		1	1			1.9
		amb	ballistite	55 clamp	5			[illegible]	1		12
		[illegible]	ballistite	90 mm	[illegible]			[illegible]			[illegible]
		40	[illegible]	clamp	3			[illegible]	1		[illegible]
		30	[illegible]	std	4			2	2		13
		[illegible]		std	2		2				[illegible]
		90		std	2		2				1
		[illegible]		std [illegible]	5		5				1
		40		std [illegible]	3		2	1			3
		[illegible]		std crk [illegible]	1		1				1
		[illegible]	ballistite	std [illegible]	3		3				1
[illegible]		amb	ballistite	std	2		2				1
		amb	SR 886	std	3		3				1

There was very little reaction in this test. Three out of the eight samples vented and blew off an end cap despite the heavy clamping that was employed. These results indicate that RU 67 has slightly lower explosiveness than RU 61 and RU 63 but this could be a consequence of the confinement employed.

Fragment Attack Test UK

Test description see NATO AOP 7 201-06-003

Degree of Reaction	Observation
0	No visible sign of reaction after penetration of the septum by the projectile
1	Hint of a burning reaction which has faded rapidly, no obvious consumption of explosive
2	Detachment of the septum, up to 20 % of explosive consumed
3	Septum detached, vehicle intact or broken into large fragments, more than 20 % of explosive consumed
4	100 % of explosive consumed in a very violent reaction characterized by breaking up of vehicle into very many small fragments showing evidence of shear failure

Results

Table 6

Round no	Septum material	Projectile velocity (ms^{-1})	Degree of reaction
10	steel	814	1
7		897	0
6		971	1
1		1099	2
9		1390	2
8		1428	2
2		1438	2
5		1506	4
4		1587	4
3		1669	4

This test was carried out according to SCC No 36 and a range of test data on other materials can be found there. While the results for RU-67 are quite good they are not exceptional for a PBX. The threshold for ignition is (very) approximately 800 m/s, which compares with approx. 900 m/s for PE4 and approx. 700 m/s for RGP (both 88 % RDX).
Reactions were relatively mild until the threshold for detonation was reached. In this test the detonation threshold is directly related to the shock sensitivity of the explosive in the large Scale Gap Test (LSGT). The value of 1500 m/s would be equivalent to a median gap of 3.3 GPa in the LSGT and, therefore, RU-67 is less shock sensitive than cast-creamed TNT but more sensitive than some other PBXs.

Discussion
The differences in the sensitivities of the two RDX-based formulations could be ascribed to the small differences in the ratio of fine and coarse RDX used to obtain a bimodal mixture; PRDX-II contains a larger fraction of fine RDX (see Table 1). Moulard found distances to initiation of about 15 mm and 23 mm (3 μs and 5 μs) for the coarse and fine RDX-based PBXes, respectively. These values were obtained for an initiation pressure of about 5 GPa. In our experiments the pressure in the plexiglass at the interface is 4.2 GPa. Assuming the Hugoniot of the PBX to be $U = 2.3+1.8u$ the pressure in the PBX is about 4.7 GPa. Since these pressures are about the same it is not surprising that the results of both tests are comparable. However, Moulard compared fine and coarse RDX formulations while in our experiments there is only a small difference in the ratio of the bimodal mixture. The great differences we observe for the different formulations could be caused by the crystal properties of the RDX, such as the crystal geometry.

From a comparison of the NOL gap test data and the initiation distances it appears that both test methods give information about different stages in the shock initiation process. The initiation distance is determined by initiating the explosive with a pressure pulse of 4.2 GPa, which is considerably higher than the pressures found in the NOL gap test. Therefore the measurements of the detonation distance probably only give information about the final stages of the pressure build-up to detonation, while the gap test results refer to the full shock initiation process.

The experiments also show that the measurements of the initiation distance and the initiation time are much more sensitive than the NOL gap test I (e.g. an initiation distance of about 3 mm is found for pressed TNT). It is our experience that small differences between different batches of a PBX can be observed with this test method. This is also confirmed by the results for the HMX-based formulations with different cross-link densities.

Sub conclusions Part I
From the results the following conclusions can be drawn:

1- The particle size distribution and possibly the geometry of the particles have a large influence on the sensitivity.

2- Although the donor system is the same, the results for the NOL gap test and the initiation distance test cannot be compared directly. However, because the latter test requires considerably fewer experiments and also seems to be more sensitive, further investigations with this test method seem feasible.

3- The sensitivity of a PBX towards shock initiation is not influenced markedly by the cross-link density variations of the plastic binder. In the deflagration to detonation mode as seen in the burning tube tests there is a visible tendency that high cross-link density give rise to more sensitive explosives. The possible explanation for this difference is the dynamic character of the shock wave; the binder act as a kind of liquid in this case, so the number of cross-links is not of importance. From the shock sensitivity work we noticed a rather large influence from the explosive particle size and shape, it was decided to study this in more detail in the second period.

PART II Influence of explosive particle size and shape.

Generally it is assumed that the polymer reduces the sensitivity of the explosive to inadvert stimuli considerably. A great deal of research has been carried out to characterize the properties of the PBX in relation to the type of polymer used [1]. In part I we have seen that the influence of the binder by its cross-link density was very minor. In part II we concentrated on the explosive particle size and shape.

Initiation of Explosives
Due to heat, friction and shock waves, explosives can decompose. If the number of decomposing explosive molecules per unit of volume exceeds a certain limit the heat of reaction will decompose the remaining explosive resulting in a self sustained reaction. Studies of the initiation of explosives have revealed that the initiation of explosives is stimulated by the imperfections in the explosive (6).
Each deviation from the ideal crystal structure causes the constituent lattice ions to free themselves more easily from their fixed positions in the lattice. The first deviation in a lattice is formed by the surface itself, the ions present in the surface have lesser bonding compared to the ions in the middle of the lattice, so they can be removed with less energy. The ions at the edges and corners can be removed even more rapidly compared to the normal surface ions.
Crystals have many natural imperfections like vacancies, edge and screw dislocations, faults, cracks; but also impurities (sometimes introduced to create a special characteristic, we call this dopants) give rise to a crystal structure with an increased mobility and reactivity.
From the above it is obvious that particle size and shape are very important features if the level of crystal faults and impurities can be kept constant be the production process.
The morphology of the high explosives used in the PBX and in particular the crystal size distribution has received a lot of attention in order to modify the sensitivity (2).
It is only recently that a more regular shape of the explosive particles is considered as a tool to decrease the sensitivity of extruded, pressed as well as cast-cured explosive charges (7).

Dyno has used a simple method to produce spheroid particles. TNO-PML has processed cast-cured HTPB-based PBXes with different batches of RDX and has measured the shock sensitivity.

To obtain a high solid load in the PBXes a bimodal mixture of coarse (about 300 μm) and fine (about 20 μm) RDX is used. In this study the shock sensitivity of PBXes with RDX taken directly from the production line and PBXes with RDX which has gone through additional processing steps to increase the spheroid character of the coarse and fine crystals have been compared.

The shock sensitivity has been determined with a rather simple gap test which determines the distance and time to detonation for different initiation pressures.

Experimental

The RDX is produced by the well-known acetic anhydride process (Bachmann process) and recrystallized in acetone.
Spheroidization of the crystals is carried out by loading angular RDX crystals in RDX saturated acetone. Next the mix is agitated and the temperature is raised and maintained at a predetermined level. When the desired spheroidization obtained by partial dissolution and erosion is reached, the suspension is discharged to a filter and washed. The reactor used has a total volume of 150 litres. It is equipped with a 6-bladed turbin agitator, 2 baffles, heating jacket, reflux condenser and a flush-mounted dumping valve. The agitator shaft has a water seal and the agitator speed can be continuously regulated.
The filter consist of a simple nutche equipped with a heating jacket and operated by vacuum.

The reactor is first loaded with a saturated solution of RDX in acetone at room temperature. The acetone has a concentration to water between 90 and 100 %. Approximately 30 kg of RDX is loaded and the agitator started. The temperature is raised to 50 °C and agitation is maintained constant for 3-5 hours. Depending on the crystal size, the agitator tip speed is set normally between 7 and 14 m/s. The suspension is discharged to the nutche and the acetone is sucked off to a filtrate tank. The filter cake is washed with water. As required, the product is finally fractioned and by mixing of fractions the required size distribution is made.

Typical scanning electron micrographs of the non treated coarse and fine sample taken directly from the production line and of the spheroidized coarse and fine sample are given in Figure 2. The particle size distributions of these samples are presented in Figure 3 and som haracteristic values are summarized in Table 7.

The coarse sample taken directly from the production line contains typical irregularly shaped agglomerates and more or less angular singular crystals. The spheroid coarse particles are more oval and small cracks are observed at the surface. The particle size distribution of both coarse samples is about the same

Table 7 Average particle size (d(0.5)) and 10 % and 90 % values of the particle size distribution of the RDX samples (μm)

sample		d (0.5)	d (0.1)	d (0.9)
coarse:	non-treated	285	185	430
	spheroidized	370	235	530
fine:	non-treated	17	5	50
	spheroidized	52	28	80

The particle size distribution of the fine samples differ considerably. The non-treated sample has a very wide distribution with a maximum around 20 μm while the spheroidized sample has a relatively narrow distribution with a maximum at 52 μm. It was not possible to obtain smaller particles. The same type of cracks as are observed for the coarse sample are observed for this fine sample.

Both coarse samples contain less than 1.0 wt% HMX while the amount of HMX in the fine samples is in between 6 and 7 wt%.

Bimodal mixtures with a coarse/fine ratio of R = 64/36 of the non-treated samples and the spheroidized samples have been used in the PBXes. Also a bimodal mixture of the spheroid coarse sample and the non-treated fine sample has been used to investigate the influence of the difference in the particle size distribution of the fine samples.
The tap density of these mixtures at R = 64/36 are 1380, 1380 and 1440 kg/m^3 respectively.

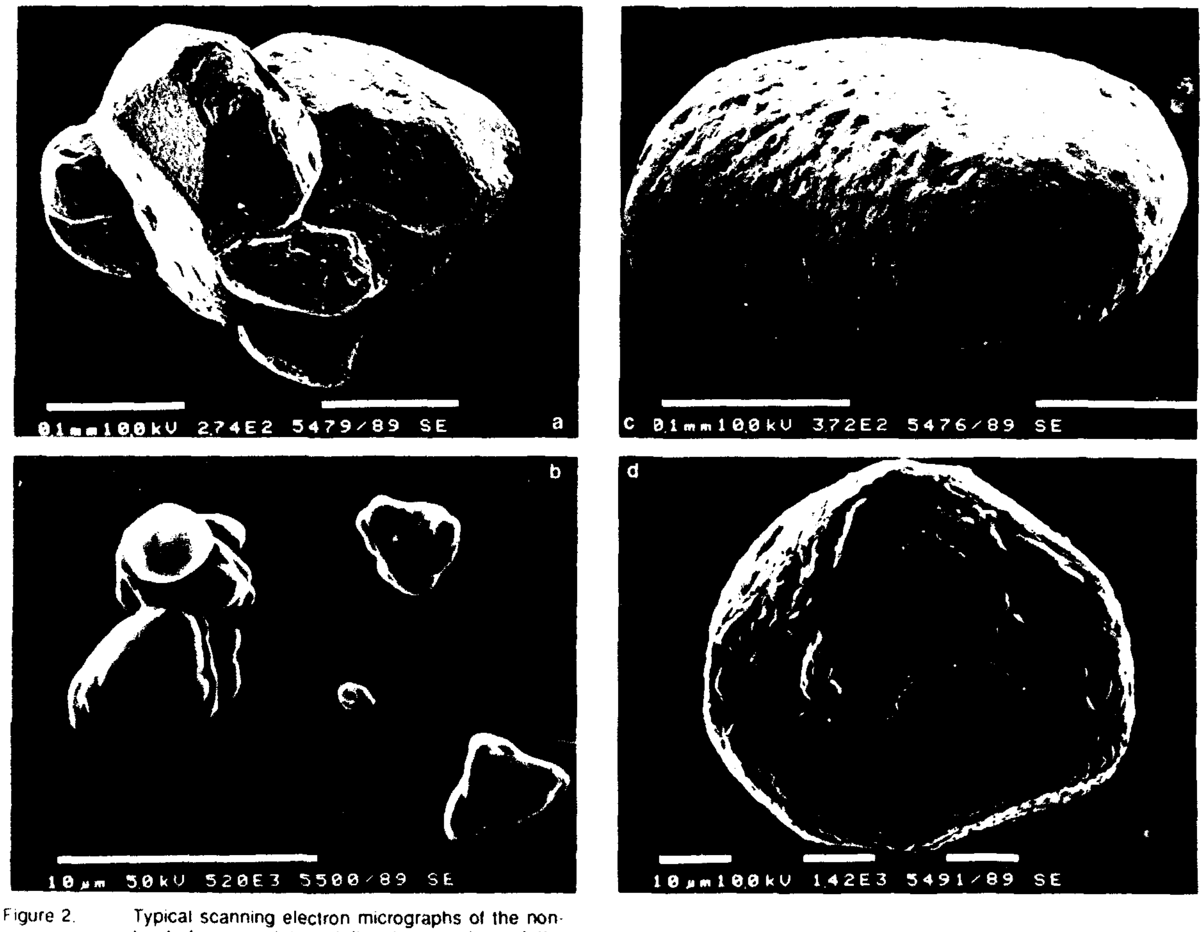

Figure 2. Typical scanning electron micrographs of the non-treated coarse (a) and fine b) sample and the spheroidized coarse (c) and fine (d) sample

A polyurethane binder (HTPB and IPDI) and a IDP plasticizer are the main ingredients of the polymer binder. Also Dantocol was added to improve the bonding between the non-polar polymer and the polar explosive crystals. PBXes were cast under vacuum and after curing the density was found to be 1580 kg/m^3 indicating that hardly any voids are present in the PBX. A more detailed description of the casting procedure can be found in (8).

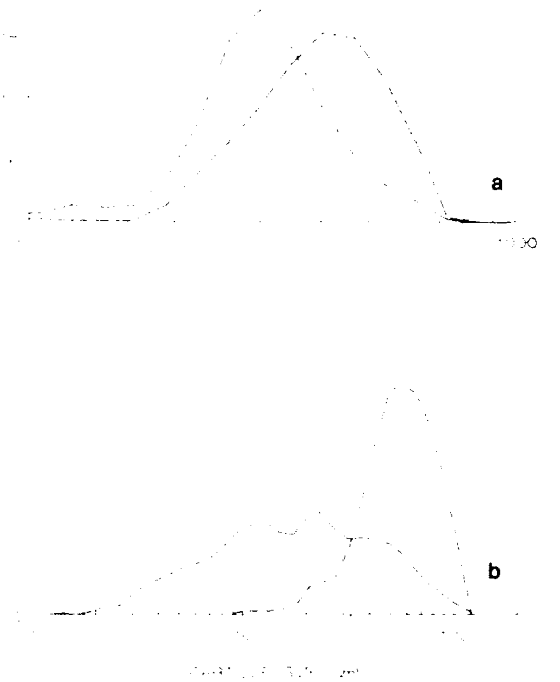

Figure 3 Particle size distribution of the coarse (a) and fine (b) samples. —— non treated and ---- spheroidized

A simple gap test is used to determine the time and distance to detonation of a bare PBX cylinder of 50 mm diameter and without any confinement. It consists of a tetryl booster (l = 50 mm, $\varnothing$ = 50 mm and ρ = 1510 kg/m^3) in combination with a plexiglass attenuator of the same diameter.

A streak camera records the shock wave through the plexiglass (back lighting) and the moment and position the shock wave enters the PBX. Also the position and time the detonation wave emerges from the side surface of the PBX is recorded by the streak camera. The initiation distance and time are determined for different initiating pressures, i.e. lengths of the plexiglass attenuator.

In contrast with the wedge test a spherical diverging shock wave is used to initiate the sample. Also the distance to detonation is not determined on the central axis but on the surface of the charge. However, from the streak recordings we learned that on arrival at the surface a detonation wave is propagating in the forward and backward direction. Since the velocities of both waves are about equal they can probably be ascribed to the spherical extension of a detonation wave starting on the central axis of the charge. For this reason it can be assumed that the results obtained with the present test will not differ considerably from wedge test results.

Results and discussion

The results obtained for the three different PBXes are presented in Figure 4 where the distances to detonation are presented as a function of the pressure in the plexiglass at the plexiglass/PBX interface. The corresponding times to detonation show the same trend and will be discussed elsewhere.

As could be expected the trend observed for all three formulations is a steady decrease of the distance to detonation with an increasing initiating pressure. At low pressures an asymptotic value is reached, below which the PBX cannot be initiated any more. At high pressures the distance to initiation seems to converge to a more or less constant value

The PBX with the non-treated RDX particles shows the shortest distances to detonation and is the most shock sensitive. For this test configuration this PBX cannot be initiated at pressures below 3.3 GPa. From experience we know that the critical pressure from this test is very close to the results obtained with the NOL Large Scale Gap Test.

The PBX with the spheroidized particles has the longest distances to detonation and its critical pressure is about 3.9 GPa for which a distance to detonation of 42 mm is found. At slightly lower pressures no initiation is observed.

These results indicate that spheroid explosive particles reduce the sensitivity of a PBX. It is assumed that the differences in the particle size distribution are to small to take care of these effects.

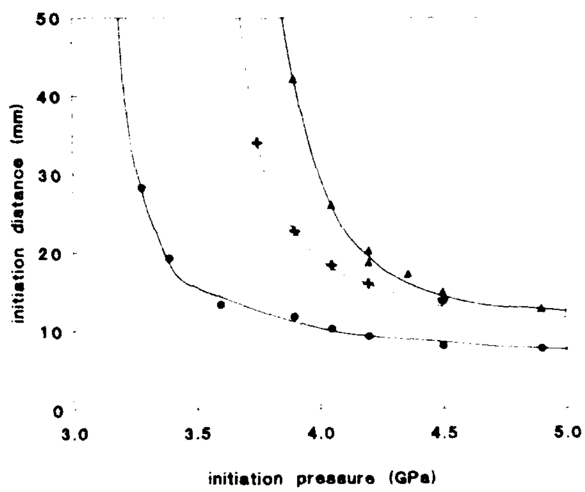

Figure 4. Distance to detonation for the PBXes with non-treated RDX (o), spheroidized RDX (D) and spheroidized coarse and non-treated fine RDX (+)

However because the particle size distributions of the fine samples differ considerably the sensitivity of a PBX with a bimodal mixture of spheroid coarse particles and non-treated fine particles has also been measured. Its sensitivity curve lies just below the curve found for the PBX with the spheroid particles with a critical pressure of 3.75 GPa. This relative increase in the sensitivity as compared to the spheroid particles is contrary to trends observed elsewhere where the sensitivity decreases with a decreasing particle size. This could also be an indication that also for the fine fraction of the bimodal mixture the particle shape is more important then the particle size.

At the moment it is not yet clear what reasons cause the shift in sensitivity.

Firstly, it might be that, despite the vacuum casting technique used, microscopical voids are formed on the surface of the crystals during the casting process. Although the densities of all tested PBXes are the same within 0.2 wt% it could be that these microscopical voids are more likely to occur on the surface of the irregularly shaped surfaces of the non-treated crystals and act as "hot spots" during initiation. The role of the small cracks observed at the surface of the spheroid particles in the initiation process is not yet clear.

A second possibility could be the content of HMX in RDX. The HMX is found both as impurities in RDX crystals and as relatively pure crystals in the fine fractions of the crystal distribution. During spheroidization HMX is dissolved leading to a lower content of HMX in the final product. This dissolving effect might also be an explanation for the cracks observed at the surface of the spheroid. The relatively low percentage of HMX at the surface of the RDX particles could be connected to the lower shock sensitivity.

A third possibility could be related to the mechanical strength of the crystals. Angular crystals will be more susceptible to shear forces than the spheroid crystal. The mechanical strength of the spheroidized samples could also be increased because these crystals have been stirred for several hours during which the crystals with less strength are crushed down and removed

Sub conclusions II

This study was started to investigate in how far the particle shape influences the sensitivity of an explosive.

Spheroid particles were obtained with a rather simple technique and also the shock sensitivities were determined with a rather simple gap test. Taken into account that the quality of the crystals could be improved by optimizing the spheroidization process and that no attempts have been made to optimize the bimodal mixture to particle size and particle size distribution the results are still impressive because the few additional steps in the production process resulted in a reduction in the shock sensitivity of 0.6 GPa. It is very likely that optimization of the production and the processing parameters will give at least a comparable reduction leading to an explosive which has an even lower sensitivity than CompB.

The spheroidization process could be improved in several ways. For example, it works best if one starts with a narrow fraction of crystals because too wide fractions will result in either crystal break-up of the largest sized crystals or less spheroidization of the smaller sized crystals. Also the reactor and stirrer design and the agitator speed could be adjusted to the specified crystal size. The temperature of the solvent and the type of solvent used will also influence the quality, i.e. the shape and the smoothness of the surface, of the crystals.

Optimization of the bimodal mixture applied could also reduce the sensitivity. From other investigations it is known that particles below 20 µm reduce the sensitivity and in this respect changes in the coarse fine ratio, within the limitations of the castability of the sample, could also reduce the sensitivity. Some results will be published in the near future.

An advantage of the increased spheroid character is the improved processibility and castability of the PBX. This might lead to even higher solid loads of about 88 % which reduces the need for energetic polymers. In how far the spheroid particles influence the mechanical properties of the PBXes is under investigation at the moment.

Conclusions

The influence of particle size and shape on the shock sensitivity of explosives is dominant to the influence of the binder by its cross link density.

This can be explained by the dominance of the explosive (88 %) in the composition; the mechanical strength will strongly be influenced by the defects in the crystals, also the bonding of the polymer to the surface of the crystals can be of importance. If the binder is only loosely connected to the crystals the explosive particles can be separated by mechanical action.

A major improvement in decrease of shock sensitivity of explosives can still be reached by making explosive particles without defects and of uniform spherical shape.

Only after that it makes sense to look after the optimum binder composition with the optimum cross link density and the best shock impedance.

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Discussion

QUESTION BY MAY, US: Would you expect this effect to also hold for much smaller particle sizes?

ANSWER: I wish I knew, but I do not know. I assume you mean 1-10 micron size spherical particles, that size is very hard to produce consistently. I don't think there are any really good methods to define these size particles.

QUESTION BY MAY, US: What would be your guess?

ANSWER: I really don't know.

Low Vulnerability Characteristics of an HMX-based Explosive

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1. SUMMARY

Cast-cured plastic-bonded explosives (PBXs) with a reduced vulnerability to unplanned stimuli are currently being developed. The explosives described in this paper are based on HMX and an inert binder. The effects of the solid loading, the particle size distribution of the HMX and the curing agent/polymer ratio on the physical, chemical, mechanical and rheological properties of the explosive were investigated.

The detonation properties of the most promising formulations were evaluated and compared to Composition B and CX-84A, a PBX developed at DREV and based on an inert binder and RDX. The shock sensitivity was measured by means of the DREV Gap Test. The detonation velocity was also evaluated. The performance of these explosives was initially evaluated by measuring their ballistic capacity, determined from the lateral acceleration of metal plates.

2. INTRODUCTION

Defence Research Establishment Valcartier has been involved in the development of cast-cured plastic-bonded explosives for approximately 20 years. This work began with explosives based on an inert binder and RDX. The objective of the work was to develop explosives with an equivalent or improved performance compared to Composition B but with an improved response to hazards. One of these explosives, CX-84A, was thoroughly studied (Refs 1, 2, 3, and 4) and was found to exhibit a lower vulnerability to unplanned stimuli. The vulnerability of CX-84A to several hazards, including fast and slow cook-off, bullet impact, heavy fragment impact and electrostatic discharge, was tested. These tests resulted in no reaction or burning only, as specified in insensitive munition requirements, for all these tests except the heavy fragment test which produced a light partial explosion. Its shock initiation sensitivity was thoroughly evaluated with the Calibrated Shock Wave Test (Ref 5) and the formulation was optimized with respect to its shock sensitivity (Ref 6). Its performance, however, was only 87% of that of Composition B as measured by the Standard Cylinder Test (Ref 7).

The RDX was replaced by HMX in order to increase the energy of the explosives but at the same time to maintain or improve their low vulnerability characteristics. Several aspects of these formulations have been considered at this time, including processing, chemical, physical and mechanical properties, shock initiation sensitivity and performance.

3. EXPERIMENTAL

3.1 Formulations

The explosive formulations discussed here were based on HMX and an inert binder. The binder was composed of R45-HT hydroxy-terminated polybutadiene (HTPB), dioctyl adipate (DOA) and toluene diisocyanate (TDI). Two different solid loadings were investigated, 84 and 85%. A bimodal distribution of Class III and Class V HMX was used and the effect of the particle size distribution was investigated by incorporating two different Class III/Class V ratios, 70/30 and 80/20, into the formulations. Two different curing agent/polymer ratios, 1.1 and 1.2, were also employed to determine the effect of this parameter on the mechanical properties of the explosive. The percentage of plasticizer remained constant at 35% of the binder for all of the formulations. The formulations are given in Table 1.

3.2 Processing

The explosives were processed in a 4CV Helicone mixer from the Atlantic Research Company. This mixer has a capacity of 1 US gal. The explosives were mixed at 60°C. The binder ingredients were mixed under vacuum and the solids were then added in three or four increments and mixed after each addition. The explosives were mixed for one hour under vacuum before the curing agent was added. The optimum mixing time was determined by measuring the viscosity of samples from a test mixture at 10 minute intervals with a Brookfield viscometer. The optimum mixing time was determined to be 1.5 hours. The viscosity of all mixtures was measured before and after the addition of the curing agent with the Brookfield viscometer. The pot life, the time between the addition of the curing agent and a significant increase in the viscosity, was determined by constantly measuring the viscosity of a sample with a Haake Rotovisco RV12 viscometer. The explosives were cured at 60°C for 3 or 4 days.

The density of the cured explosives was measured with a

Table 1: Explosive Formulations

Ingredient	Formulation 1	Formulation 2	Formulation 3	Formulation 4
HMX Class III	58.8	67.2	58.8	59.5
HMX Class V	25.2	16.8	25.2	25.5
HTPB	9.6	9.6	9.5	9.0
DOA	5.6	5.6	5.6	5.2
TDI	0.8	0.8	0.9	0.8

Quantachrome Corp. picnometer. Helium was used as the displacement gas. The hardness of the PBXs was measured with a Shore A durometer.

3.3 Characterization

The cured explosives were characterized by measuring their mechanical properties in tension with a Instron Universal Testing Instrument Model 1122. The samples were conventional JANNAF dog bones. The explosives were cast into slabs and the dog bones were cut with a die. These properties were measured at both ambient temperature and -40°C. Some samples were conditioned at -40°C for 14 days and their mechanical properties were then measured at -50°C. No significant change in mechanical properties was noted as a result of the conditioning and no embrittlement effect was observed as is expected with an HTPB binder-based explosive.

The detonation velocity of the formulations was measured by both ionization probes and streak camera on samples 5.08 cm in diameter and 15.0 cm in length. The charges were initiated by a plane wave generator of the same diameter. The ionization probes were placed at 5.08 cm intervals and the velocity between each of the probes and between the first and last probe were measured.

The shock initiation sensitivity of the formulations was evaluated by the DREV Gap Test on samples 3.18 cm in diameter and 7.62 cm in length. Two tetryl pellets, 1.59 cm in diameter and 1.75 cm in length, served as the donor. The barrier in the DREV Gap Test is made of aluminum.

The ballistic capacity of the explosive formulations was measured by the lateral acceleration of metal plates propelled by the explosive's detonation front. The ballistic performance of the explosive is defined as the energy transferred to the plate. The detonation velocity, metal plate angle, and detonation gas angle are measured experimentally, and the optimal energy transfer, optimal energy efficiency, Richter coefficients, chemical energy and the Chapman-Jouget pressure are calculated (Ref 8). This test was developed in France (Ref 9) and is used as a preliminary step in the characterization of an explosive's performance before more extensive tests such the Standard Cylinder Test are carried out. The explosive samples were machined into slabs 26.2 ± 0.05 cm by 8.4 ± 0.005 cm and 2.0 ± 0.005 cm thick. The charges were initiated with a line wave generator (Ref 10). The detonation velocity was measured by ionization probes. The metal plate and detonation gas angles were determined from images obtained from a flash X-ray system.

4. RESULTS

The viscosity of the explosive mixtures for the formulations outlined in Table 1 are given in Table 2. It can be seen that the final viscosity is slightly higher for the formulation loaded with 85% HMX, 4.0 kP compared to 1.6 kP for 84% HMX loading. The effect of particle distribution on the viscosity for formulations with 84% solid loading is less pronounced. The viscosity increases from 1.6 kP for a Class III/Class V ratio of 70/30 to 2.6 kP for a Class III/Class V ratio of 80/20. Some initial studies with 85% HMX loading indicate that the effect of particle distribution is more significant at this loading. The viscosities before the addition of the curing agent fall in the range 12.0 to 10.8 kP.

The pot life for these formulations is also given in Table 2. Once again the formulation with 85% HMX loading has a pot life which differs significantly from those for the other formulations. The pot life for the formulation with 85% HMX loading is 137 min compared to 285 min for a similar formulation with 84% loading; the pot life for the formulation with 85% solid loading being approximately half of that measured for the others. Additional studies have confirmed that these formulations have a shorter pot life when 85% solid loading is used instead of 84%. The pot lives for the other formulations fall within a shorter range of values, 285 to 224 min, the shortest being that for the formulation with the higher Class III/Class V HMX ratio and higher viscosity.

The hardness of these formulations is fairly constant and falls within the range 68 to 63 Shore A. The highest value

is that for the formulation with the higher curing agent/polymer ratio; however, as a preliminary evaluation, these differences could not be considered significant. The density of these formulations is in the range of 1.62 to 1.63 Mg/m^3, the density of formulations with 85% solid loading being slightly higher than those with 84% HMX loading.

The results for the mechanical properties testing are given in Table 3. The values given are for the maximum stress and the elongation at rupture, measured in tension. The particle distribution in this case had a much greater effect on the value for the maximum stress than on the elongation of the sample. The elongation decreased from 26.07 to 24.98% when the HMX Class III/Class V ratio was increased from 70/30 to 80/20; however, the value for the maximum stress decreased from 0.62 to 0.53 MPa. Increasing the ratio of the curing agent/polymer ratio from 1.1 to 1.2 resulted in an increase in the value for the maximum stress, from 0.62 to 0.69 MPa, and a significant decrease in the elongation of the explosive, from 26.07 to 15.71%. An increase in the solid loading produced explosives with a lower elongation, 26.07% for 84% HMX loading compared to 20.35% elongation for a similar formulation with 85% solid loading, without effecting the value for the maximum stress.

Changing the curing agent/polymer ratio seems to have the most dramatic effect on the elongation of the cured explosives. The particle size distribution appears to be slightly more effective in changing the value for the maximum stress than the other formulation parameters. A decrease in temperature results in an almost doubling of the value for the maximum stress but has very little effect on the elongation.

The detonation velocity for formulations with 84 and 85% loading are compared with those for CX-84A and Composition B in Table 4. There is an significant increase in the detonation velocity of formulations with 84 and 85% HMX loading compared to CX-84A and Composition B. The detonation velocity for the HMX-based formulations are 8351 and 8200 m/s for formulations with 85 and 84% solid loading respectively, compared to 7908 and 7892 m/s for CX-84A and Composition B respectively.

Ballistic capacity experiments have also been conducted on a formulation with 84% loading. These results are compared to those for CX-84A and Composition B (Ref 9) in Table 5. The detonation velocity of 8197 m/s is in agreement with the value measured on cylinders 5.08 cm in diameter using both streak camera and ionization probes. The detonation pressure was evaluated at 27.9 GPa. This

Table 2: Physical Properties of Formulations

Formulation	Viscosity (kP)		Pot Life (min)	Hardness (Shore A)
	Before Curing Agent	After Curing Agent		
1	11.2	1.6	285	63
2	12.0	2.6	224	67
3	10.8	2.0	258	68
4	11.6	4.0	137	65

Table 3: Mechanical Properties of Formulations

Formulation	Room Temperature			-40°C		
	Stress (MPa)	Elongation (%)	Modulus (MPa)	Stress (MPa)	Elongation (%)	Modulus (MPa)
1	0.62	26.07	5.02	1.24	22.92	23.652
2	0.53	24.98	4.95	1.14	24.24	19.30
3	0.69	15.71	8.71	1.35	17.48	17.48
4	0.62	20.35	6.62	1.02	16.89	26.79

Table 4: Detonation Velocities of Formulations

Explosive	Detonation Velocity (m/s)
Formulation 1	8200
Formulation 4	8351
CX-84A	7908
Composition B	7892

Table 5: Explosive Characteristics from Ballistic Capacity Evaluations

	Formulation 1	CX-84A	Composition B
ρ (g/ml)	1.618	1.554	1.717
D (m/s)	8197	7908	7892
P_{CJ} (GPa)	27.9	25.4	27.9
E_c (J/g)	4146	4008	4586
KE (J/g)	1114	1076	1230

ρ - density
D - detonation velocity
P_{CJ} - detonation pressure
E_c - chemical energy
KE - maximum kinetic energy

is the same as the value obtained for Composition B and is higher than the value of 25.4 GPa obtained for CX-84A. The kinetic energy appears to be lower than that of Composition B; Composition B having a kinetic energy of 1230 J/g compared to 1114 J/g for the formulation with 84% HMX, but higher than that of CX-84A (1076 J/g). However, further experiments, such as the Cylinder Test, are needed in order to evaluate the performance of these explosives more precisely.

The shock initiation sensitivity was evaluated with the DREV Gap Test for two formulations with 84% loading. One of these formulations had an HMX Class E/Class C ratio of 30/70 and the other had a ratio of 20/80. These values are compared to those for Composition B and CX-84A (Ref 1) in Table 6. The barrier thickness of 1.16 cm for the shock sensitivity of CX-84A is higher than the value for the final formulation. Improvements were made in the formulation to reduce the shock sensitivity; however, the sensitivity was evaluated with the Calibrated Shock Wave Test (Ref 6). There is a significant improvement in the shock sensitivity of these formulations. The barrier thickness for formulations with 84 and 85% HMX loading were 0.79 and 0.73 cm respectively, compared to 1.14 and 1.16 cm for Composition B and CX-84A respectively. A small difference can also be noted as a result of a change in particle size distribution.

5. DISCUSSION

The development of an insensitive explosive must be considered not only from the point of view of the properties of the final products but also from a processing viewpoint and for this reason these characteristics have been included in this evaluation. Since this is a preliminary evaluation of this system of explosives, the initial objective was to determine the formulation limits with respect to processing and the resulting sensitivity and performance characteristics.

Since these formulations are intended for cast-cured PBXs, the viscosity of the mixture is a very important consideration in their processing. The particle size distribution did not have a great effect on the viscosity of the mixture for 84% HMX loading. Viscosity measurements of 2.6 kP for a HMX Class III/Class V ratio of 80/20 and 1.6 kP for a HMX Class III/Class V ratio of 70/30 were determined. A greater effect is observed for formulations with 85% solid loading since the viscosity is

Table 6: Shock Initiation Sensitivity

Explosive	Gap Thickness (cm)
Formulation 1	0.79
Formulation 2	0.73
CX-84A	1.16
Composition B	1.14

already higher and therefore the particle distribution has a greater effect on the viscosity.

The pot life of 137 min for the formulation with a higher solid loading represents a value significantly lower than that for formulations with 84% HMX loading. This value is almost half of that for formulations with 84% loading; however, either value in this range is considered acceptable. All the values for the hardness fall within a small range, 68 to 63 Shore A, and therefore this need not be considered when finalising the formulation. Therefore, the processing of formulations having parameters within this range of values is possible; the only restriction might be on the particle distribution at 85% HMX loading which could present a problem in optimizing the sensitivity characteristics of the explosive formulations.

Since the mechanical properties of the explosive affect their vulnerability, the optimization of these properties is an important step and gives another indication of the limitations and effects of various formulation parameters on the explosive properties. The effect of reducing the percentage of fine particles in the particle distribution is to reduce the maximum value of the stress from 0.62 to 0.53 MPa, for formulations with HMX Class III/Class V ratios of 70/30 and 80/20 respectively, without affecting the elongation significantly. This must be considered if the particle distribution must be modified to meet sensitivity requirements since further modifications to the formulation would be necessary to compensate for this. Increasing the solid loading results in a decrease in the elongation, from 26.07 to 20.35% for formulations with 84 and 85% HMX loading respectively, without affecting the value for the maximum stress which remained at 0.62 MPa. Increasing the curing agent/polymer ratio results in a significant decrease in the elongation of the explosive, from 26.07 to 20.35%, for a 10% increase in the curing agent/polymer ratio. In addition to this, the value for the maximum stress increases from 0.62 to 0.69 MPa for the same increase in curing agent/polymer ratio. Experience with CX-84A has indicated that the elongation for Formulations 1 and 2 should result in explosives with a low vulnerability (Ref 6); however, it will be necessary to increase the value for the maximum stress.

There is a significant increase in the detonation velocity for formulations loaded with 84 and 85% HMX compared to Composition B and CX-84A. These values have increased from 7900 m/s for Composition B and CX-84A to 835[illegible] and 8200 m/s for formulations with 85 and 84% HMX loading respectively.

An initial evaluation of the performance of the explosive was carried out with a ballistic capacity test. There appears to be some improvement in the performance of the HMX-based formulation compared to CX-84A, the kinetic energy being 1114 J/g for the HMX-based formulation and 1076 J/g for CX-84A, but this must be further evaluated with a more precise test. The detonation pressure determined in this evaluation was the same as that for Composition B, 27.9 GPa, which is higher than the value of 25.4 GPa determined for CX-84A. It is also necessary to evaluate a formulation with 85% HMX loading in order to determine if the increase in loading will result in a significant increase in performance. This, along with the processing and sensitivity data, must be considered when finalizing the formulation.

The particle distribution does affect the shock initiation sensitivity of the explosive as can be seen from the increase in barrier thickness from 0.73 to 0.79 cm for formulations with HMX Class III/Class V ratios of 80/20 and 70/30 respectively. This must be investigated further and the effect of an increase in solid loading must also be evaluated.

6. CONCLUSIONS

Further work must be carried out to evaluate the shock sensitivity and performance of these formulations more precisely. In particular, formulations with 85% loading must be evaluated to determine the effect of the increase in solid loading on the shock initiation sensitivity and the performance. More precise evaluations must be conducted with the Standard Cylinder Test and the Calibrated Shock Wave Test in order to optimize the formulations with respect to processing, shock sensitivity, performance and finally the vulnerability of the explosive.

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Discussion

QUESTION BY LENBERGER, FRANCE: Have you utilized rubber plates so as not to deteriorate the test facility?

ANSWER: We have never used rubber plates at the DREV. Soft steel plates permanently protect the concrete walls and we have used wood for additional protection.

ESD TRAITS OF BULK PROPELLANT UNDER PRESSURE

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ABSTRACT

Since the Pershing booster motor incident occurred in 1985, much has been learned about how to test for electrostatic discharge (ESD) characteristics and what factors influence ESD initiation sensitivity for solid propellants. Small propellant samples have shown enhanced ESD sensitivity when placed under pressure. Since changes in bulk solid propellant ESD traits under the influence of elevated pressures were not found in our literature surveys, equipment was fabricated so that pressure effects on ESD behavior of a hydroxy terminated polybutadiene (HTPB) propellant could be observed. In addition, a limited additive study was conducted to see if large ion salts could reduce the ESD initiation sensitivity of a sensitive HTPB propellant.

1. BACKGROUND

ESD initiation is a significant hazard with some hydrocarbon binder solid propellants filled by ammonium perchlorate (AP) and aluminum (Al), especially, hydroxy terminated polybutadiene (HTPB) propellants. This hazard was dramatically brought to United States (US) attention with the case bursting "Pershing" incident in Germany. The violent event involved a HTPB propellant installed in an electrically nonconducting motor case. Some questions asked following the incident were: Why didn't the ESD tests that were used indicate the degree of hazard? How could we adequately test to see if ESD initiation was a significant hazard? Were other propellant types ESD sensitive? What were ways to diminish or remove propellant ESD hazards?

Our laboratory (Now a part of the Phillips Laboratory and formerly named the Air Force Rocket Propulsion Laboratory and the Astronautics Laboratory) was one of several laboratories that initiated solid propellant ESD studies. Goals were to find adequate test methods for observing ESD sensitivity, to rank ESD sensitivities of various solid propellants, to discover what variables influenced ESD behavior, and to determine procedures for reducing ESD risks. These studies are continuing.

The US ESD test at the time of the Pershing incident had been adapted from procedures used with pyrotechnic and ammunition primer materials. Solid propellant sample sizes were not specified on the basis of their suitability for exhibiting ESD sensitivity. In our laboratory this was interpreted to mean that very small sample sizes could be used. Samples that we tested at that time were about 12.7 mm (millimeter) in diameter with thicknesses about 0.6 to 0.8 mm. Our criteria for a failure was the appearance of smoke and/or fire. Since smoke or fire never appeared in our solid propellant testing with the small disc samples, lack of ESD risk was assumed.

A much better ESD test was what we call the "French test" (Ref. 1). French investigators at SNPE (Societe Nationale des Poudres et Explosifs, Kent and Rat) employed large samples that provided smoke and fire indications of solid propellant ESD sensitivities. Their samples were 90 mm diameter by 100 mm length cylinders. These samples were roughly 7000 times larger than those employed in our initial ESD test method.

Our laboratory adopted the French test and found after some experimentation that indications of bulk solid propellant ESD sensitivity could be obtained with more sensitive propellants using cylindrical samples as small as 19 mm diameter by 38 mm length (Ref. 2). These samples were less than one

fiftieth the mass of the original French propellant sample. See Figure 1 for ESD sample size comparisons. This smaller propellant sample size was adopted for use at our laboratory because our small experimental mix capacity made fabrication of an adequate number of ESD propellant samples using the larger sample size difficult. The primary difference in test performance was that the larger cylindrical samples burned to completion much more frequently than the smaller samples. A brief bright burst of flame from one or more locations with the formation of cracks was the typical positive response of the smaller samples when they reacted to electric charging at ambient pressures. Phil Gibson at our laboratory also showed that cylindrical propellant samples 9.5 mm diameter by 25 mm in length were too small to produce smoke and/or fire indications under conditions similar to those that gave positive responses with the 19 mm diameter by 38 mm length cylinders (Ref. 2). Thus, the problem with the earlier US ESD test was that thin disc propellant samples at normal ambient pressures were too small to give smoke and/or fire indications. Later we came to the conclusion that abrupt passage of current (electric breakdown) through a propellant sample always provides the possibility of ignition. Electric breakdown became our minimum measure of a positive ESD response. Electric breakdown had often occurred in the earliest ESD tests without smoke but with very minor material ablation noted in some instances. It is difficult to specify how sensitive a propellant will have to be before it becomes an appreciable ESD accident risk. However, laboratory ESD solid propellant tests have been only crudely related to rocket motor hazards by determining if a propellant under test is more or less ESD sensitive than a propellant involved in a prior accident.

Investigation into changes in threshold initiation or breakdown voltages of bulk HTPB propellant as a function of applied pressure seemed a desirable area to explore. Bulk propellant ESD hazards appeared to be more appropriate for rocket motor hazards where large pieces of propellant are installed rather than for thin samples. In any event, a pressurized bulk propellant study would complement the work completed by Thiokol Corp with thin (0.69 mm thick) sheet samples of a HTPB propellant (Ref. 3). In the Thiokol study 0.69 mm thick samples of a HTPB propellant were mechanically squeezed between metal plates while adjustable voltage charges from a capacitor circuit were applied. Pressures ranged from normal ambient pressure up to 55 atmospheres (810 psig). Threshold initiation voltages were recorded for a number of thin HTPB propellant sheets over the pressure range as shown in Figure 2. Values ranged from roughly 5000 to 6000 volts at ambient pressure down to roughly 600 volts at 55 atmospheres (atm). Thus, the main interest in the bulk HTPB propellant study was to see if large samples would exhibit an order of magnitude decrease in threshold initiation voltages over a similar pressure range as did the thin solid propellant samples.

2. EQUIPMENT DESCRIPTION

Several features were desired in designing pressure application equipment for conducting ESD studies on a HTPB propellant. (1) A robust system that could be reused fairly frequently without equipment failures. (2) A test system that minimized parts replacements and refurbishment efforts during a number of test trials. (3) A system that could completely contain a violent sample explosion if it occurred. In this case the subscale bulk propellant ESD test sample was desirable because it was small enough to be contained in a modest sized chamber if explosive behavior was exhibited. (4) Capabilities to at least 40 KV and 68 atm (1000 psia) pressure. (5) Use of nitrogen gas pressure rather than mechanical pressure.

Figure 3 shows a cross sectional view of the ESD test chamber that resulted from the considerations above. Descriptions of the chamber parts are given below.

The cylindrical chamber was constructed from 3140 alloy steel. Internal dimensions with end plates installed were 178 mm internal diameter (ID) by 424 mm length. This was a volume of about 10.5 liters. Chamber walls were about 15 mm thick. A heavy electric conductor led from the cylindrical chamber to the ESD grounding system.

End plates were made from 304 stainless steel alloy. The upper end plate was 76 mm thick and the lower end plate was 35 mm thick. Segmented lock rings inserted into cylindrical chamber grooves were used to hold the end plates in place. Double O-rings were used to avoid gas leakage around the end plates. O-rings were lubricated with a thin film of a heavy Krytox oil (DuPont, perfluoropropylene oxide). Use of hydrocarbon and silicone oils resulted in such a high friction load following propellant burning that the upper end plate was very difficult to remove. Perhaps, the Krytox oil had a lower capacity for dissolving hydrogen chloride gas from propellant combustion than the other lubricants. The lower end plate rested against a hard aluminum alloy ring grooved to a depth that would fail in shear allowing the lower end plate to be forced out of the chamber if internal pressure exceeded about 350 atm. This seemed an unnecessary safety feature for the ESD tests since test pressures did not exceed 69 atm.

Nylon electrode insulators were used to encase 6.4 mm diameter, 304 stainless steel, electrode rods. The insulators extended beyond the end plates 51 mm or more to help prevent sparks arcing from the electrode rods to the end plates at test voltages up to 40 KV. Insulator outer surfaces were tapered as they passed through the end plates. With internal diameters of 38 mm and exiting diameters of 25 mm the insulators were prevented from being blown out during testing. The inside end of the upper electrode insulator was preferably covered with two layers of thin Teflon tape (12.7 mm width). Teflon tape is often used as a thread lubricant in our experimental equipment. This was found to be desirable when the upper insulator became a short circuiting element due to charring upon exposure to gaseous combustion products during previous tests where samples burned in the pressure chamber. Ordinarily, the Teflon tape was reinstalled about every other ESD test under pressurized conditions that produced bulk sample combustion. RTV silicone glue was used to seal the electrode insulators into the end plates. RTV adhesive was also used to seal around the electrode rods.

Electrode configurations were relatively complicated as shown in Figure 3. At the bottom of the chamber the lower electrode started as a 6.4 mm diameter rod of 304 stainless steel alloy that had an integral 3mm thick plate of 12.7 mm outer diameter located 6.4 mm from one end of the rod. At the other end of the rod a 3.2 mm diameter hole 12 mm deep was drilled. This hole served to fit with a banana plug connector attached to the ground wire that would be attached during ESD testing. The lower electrode rod was passed through the bottom insulator so that the integral plate remained inside the chamber. The plate prevented electrode blowout. Resting atop the inside end of the lower electrode rod was an electrode extension rod of 12.7 mm outer diameter containing a 6.5 mm cavity to fit over the upper end of the lower rod and terminating in a 6.4 mm diameter end for a distance of 6.4 mm. Placed over the 6.4 mm end of the extension rod was a 6.4 mm thick plate of 102 mm diameter made of 304 stainless steel alloy. A 6.5 mm hole was drilled through the center of the plate to admit the 6.4 mm extension rod end. These loose connections had to be polished frequently to remove high resistance solid corrosion products.

On top of the plate a graphite cup was set to contain the propellant samples during test. Graphite's electrical conductivity allowed it to form the sample contacting part of the lower electrode system. Graphite's heat resistant qualities also permitted propellant samples to burn without damage to either the graphite cup or the chamber walls. The graphite cup was 177 mm outer diameter (OD) by 44 mm thick at the perimeter. A cavity was formed in the graphite by reducing the thickness to 13 mm in the center for a diameter of 54 mm. Eight 25 mm half diameter channels were machined vertically around the cup outer edge for facile passage of gases around the graphite cup.

The first upper electrode system had a 304 stainless steel alloy, 6.4 mm diameter rod passing through an upper electrode insulator. The upper rod through the insulator terminated with an integral 3 mm thick plate having a US number six threaded hole into the

rod at the plate end and a 3.2 mm diameter hole of 12 mm depth drilled into the other end of the rod. The 3.2 mm hole had a banana plug connector attached to the high voltage system inserted in it during testing. The threaded hole allowed a US number six screw to hold a wire connector on the electrode rod attached to a short length of flexible, multistrand steel wire. As with the lower rod passing through the nylon insulator, the upper electrode rod was put through the insulator so that the integral plate was inside the test chamber. At the other end of the multistrand steel wire, a rectangular steel plate (about 25 mm by 19 mm by 1.25 mm thick) was attached using another wire connector and a US number six bolt.

A terminal part for the initial upper electrode system was an upper sample contact measuring 25.4 mm outer diameter by 19 mm thick. This cylinder was made of 304 stainless steel alloy. The corner of the cylindrical contact on the side resting against the propellant was rounded with a radius of 3mm to inhibit corner discharges. A 3.2 mm hole was put through the center of the propellant contact to enable acceptance of a banana plug attached to a magnet structure as described below.

The remaining bulk sample upper electrode parts were a rectangular magnet (about 22 mm by 22 mm by 5 mm thick) secured horizontally to the bolt end of a banana plug connecter that was inserted into a 3.2 mm diameter hole drilled into the center of the cylindrical stainless steel sample contact. Once a propellant test sample and upper electrode contact with magnet structure was placed in the center of the graphite cup, this flexible wire structure, steel plate, and magnet attached to a stainless steel contact served as a magnetically formed electrical path to the samples.

When electric arcing around the sample was suspected during ESD testing of 0.64 to 0.69 mm thick propellant samples, an adjustable rod upper electrode system was fabricated and used in place of the upper electrode system described above as shown in Figure 4. With this electrode the diameter of the upper propellant contact was reduced to 9.5 mm diameter in place of the previously used 25.4 mm diameter contact. As before a 6.4 mm diameter upper electrode rod passed through the nylon insulator. It was much longer (350 mm) than the earlier electrode rod. No adhesive was used to seal the electrode rod in its path through the nylon insulator. For sealing, the new upper electrode rod was passed through a 6.4 mm diameter Swagelok tube fitting that was threaded into the outlet end of the nylon insulator. The Swagelok fitting was equipped with Teflon ferrules that permitted the electrode rod to slide through the fitting when loosened and to be securely sealed when tightened. The inside end of the rod was threaded and an internally threaded 304 stainless steel sleeve of 9.5 mm outer diameter by 12 mm length was screwed onto the threaded end. The 9.5 mm sleeve prevented electrode blowout during pressurized operations. In addition, the 9.5 mm diameter sleeve and rod end was the electrode part contacting propellant samples during subsequent tests. As before, the opposite end of the electrode rod contained a 3.2 mm diameter hole 12 mm deep so that it could accept a banana plug attached to the electric system hot line. This second upper electrode system was placed in the retracted position when the upper end plate was being moved. Prior to testing the upper end plate was installed, the Swagelok fitting was loosened, the rod depressed until contact was made with the propellant sample, and the Swagelok fitting tightened. After the hot line banana plug was inserted into the outside end of the electrode rod, the system was ready for electric charge experimentation. This upper electrode system was an improvement since it contained fewer parts and intervening connections did not corrode. Another difference with the new electrode system was that threshold breakdown voltages seemed to be approximately half that with the other upper electrode system. No sketch of the new upper electrode system is provided.

As can be seen in Figure 3, a gaseous nitrogen feed line and an exhaust line were connected to the test chamber through the lower end plate. The operation of these lines were controlled by remote control valves placed in the lines. A pressure sensor was connected into the nitrogen inlet line between

the nitrogen feed control valve and the chamber. A 0.7 mm wall 25 mm outer diameter stainless steel tube about 125 mm long was held by a fitting to the chamber outlet hole through the lower end plate. A stainless steel wire mesh screen was inserted into the 25 mm tube next to the chamber outlet port. Glass wool was stuffed into the 25 mm tube atop the wire mesh to help filter out aluminum oxide particles carried by gases exhausting from the chamber following operation of the chamber where a propellant sample burned. The glass wool filter system was added when it was found that aluminum oxide particles seriously shortened the service life of the remote control exhaust valve.

3. DISCUSSION

During ESD testing, a HTPB propellant sample was placed standing at the center of the graphite cup, the upper end plate was installed, and contact made with the upper electrode system to the propellant test sample either magnetically or by direct electrode rod contact depending upon the upper electrode structure used. Test pressure was adjusted to a predetermined value, and, through a switched capacitor operation, the sample was pulsed up to 10 times with a preset relatively low voltage. If no sample breakdown occurred, the preset voltage was typically raised 1000 volts for the bulk sample testing and the pulse operation repeated. Voltage steps for the thin propellant sheets were 100 volts. Increasing step increases in imposed voltages were continued until the oscilloscope registered a large voltage drop with a massive current surge (electrical breakdown). Under elevated pressures bulk samples (38 mm long) always burned to completion. With the propellant burning a temporary pressure increase of about 40 atm occurred and a thermocouple placed against the outside of the test chamber wall registered a short lived temperature rise of 20 degrees Celsius or more. These were all indications of a positive test. With thin samples and bulk samples under one atm conditions, only physical inspection of samples and voltage and current changes indicated propellant electric breakdown. The lowest voltage that would provide an electrical breakdown of the propellant sample was recorded. Some variations in threshold voltages were observed, and the lowest voltage recorded for any number of samples under the same pressure and temperature conditions was called the threshold initiation voltage or threshold breakdown voltage.

For the purpose of readily observing the effects of temperature and pressure upon propellant ESD characteristics an ESD sensitive HTPB propellant was formulated. This was given the name, ESD-1. This propellant contained 12% HTPB binder, 10% each of Valley Metallurgical H-3 (3 Micron) and Alcan MDX-65 (6 micron) spherical aluminum, and a bimodal distribution of 200 and 16 micron ammonium perchlorate. This was a good propellant in most of its characteristics, except that it was more ESD hazardous than desired for use in rocket motors. A detailed formulation is provided in Table I. The high ESD sensitivity came primarily from its small aluminum particle sizes (6 and 3 micron), its high aluminum content (20%), and its high solids loading (88%). If less ESD sensitive propellant were desired, the formulation would use a larger size of spherical aluminum, a lower aluminum content, and a lower total solids content.

A large number of test samples were cut from a block of ESD-1 propellant. These were cylinders of 24 mm diameter with 38 mm lengths. Some thin propellant sheets of 0.64 to 0.69 mm thickness were cut from the cylinderical samples to provide thin samples for testing to see if our results would be generally similar to that obtained by the Thiokol Corporation in their HTPB propellant tests. Since Thiokol was using a different propellant formulation and held thin propellant samples under mechanical force between stainless steel plates, comparison of the results under similar but gaseous pressures was desired (3).

When ESD testing started at the existing ambient pressure and temperatures found in the Mojave Desert during June and July, breakdown voltages often exceeded 30 KV. This was unexpectedly high and may have been due to the following factors: (1) The ESD electrical test circuitry had been recently

replaced using new components so that voltage capability could be raised from about 40 KV to near 100 KV. This included removal of a series resistor of 1000 ohms and changing from a 9.5 mm diameter electrode sample contact to a 25.4 mm diameter electrode sample contact for the hot electrode. (2) Much higher ambient temperatures were being experienced, 25 to 42 degrees Celsius, than during earlier fall and winter testing which ranged from 5 to 20 degrees Celsius. During one working day ambient temperatures could often vary from about 25 to 38 degrees Celsius. As a result a temperature controlled recirculating air system was connected to a cardboard box installed around the test chamber. This allowed testing at relatively constant temperatures independent of the outside ambient temperatures. After minimal experimentation, test temperatures were maintained near 10 degrees Celsius since it was preferred to test below 30 KV.

Figure 5 contains 69 atm (1000 psig) data exhibiting a declining trend for threshold ESD-1 bulk propellant initiation voltages as test temperatures were reduced. Repeatability of threshold breakdown voltages were highly variable, but average values declined with decreases in sample test temperatures. A series of one atm trials showed a similar declining trend for threshold initiation voltages as test temperatures were reduced. It appeared that threshold breakdown voltages were reduced from roughly 27 KV to 15 KV in going from 35 to 10 degrees Celsius, respectively.

ESD-1 24 mm ameter by 38 mm long propellant cylinders were tested at a variety of pressures. Minimum breakdown voltages for each sample were recorded. Figure 6 shows a plot of this data. Some of the data points are the same result for two experiments. Although the data show rough variation in threshold breakdown voltages at any pressure, a broad band trend toward lower initiation thresholds with increasing pressure is apparent. In contrast to the Thiokol thin propellant sheet data where threshold voltages declined to about one tenth of the one atm values under about 55 atm conditions (Ref. 3), bulk propellant minimum breakdown voltages seemed to diminish only to about half the one atm values. From a safety standpoint the refreshing conclusion is that bulk propellant ESD threshold propellant initiation levels do not get overly sensitive at elevated pressures. Even at 69 atm the sensitive bulk propellant did not react until the voltage was many KV. This means that as pressure is applied to bulk propellant structures the ESD hazard thresholds can stay at relatively high voltages.

Following the initial pressurized bulk propellant experiments, thin sheets of ESD-1 HTPB propellant were cut from test cylinders. Test samples were selected that had thicknesses in the range of 0.64 to 0.69 mm. During initial thin propellant sample testing at one atm, electric breakdowns at one KV were observed. Examinations of the samples under test did not show any burn spots or cracking that would be expected if an electrical breakdown of the thin propellant sheets took place. Since the voltages seemed close to that required to jump around the propellant sample, a new upper electrode rod structure as described above was fabricated and installed. With the new 9.5 mm diameter upper electrode propellant contact, rather than the previously used 25.4 mm electrode contact, about 7 mm of air gap was added to the path needed for arcing around the propellant sample. Table II exhibits the results of two pressurized tests and two tests at ambient pressure. Electrical breakdowns of the ESD-1 thin sheets occurred at 500 and 700 volts under 46 (670 psia) and 38 (550 psia) atm pressures, respectively. For the 500 volt breakdown only a minor dark stain and a small pit were visible evidence of propellant breakdown in the pressurized test. Complete sample burning was obtained following the 700 volt breakdown. Tests at one atm showed thin sheet propellant electrical breakdown failure twice at 1400 volts. No complete sample burning was noted. When electrical breakdown occurred in the one atm tests, small smoky stains and small black pits were observed on the thin propellant samples at the points where breakdown took place. These breakdown results were quite different from Thiokol's results obtained with their 0.69 mm sheets of HTPB propellant (Ref. 3). First, the 1400 volt breakdowns indicated that the ESD-1 propellant was more electrostatic sensitive than the Thiokol HTPB propellant. Second,

the violence of reaction by the thin ESD-1 propellant sheets under elevated gas pressures at electric breakdown was much milder than obtained in the Thiokol study with propellant samples squeezed between metal plates. When Thiokol's thin samples between plates under mechanical pressure had electrical breakdown, loud explosive behavior was usually observed (Ref. 3). This was probably due to combustion gases producing much higher pressures in small regions around breakdown points than could be obtained under pneumatic conditions. Third, the ratio between threshold initiation voltages at one atm and roughly 50 atm pressure conditions was about 2 to 3 by the gas pressurized tests versus Thiokol's ratio of about ten. Squeezing of propellant samples to smaller thicknesses would be expected to further decrease threshold voltages under pressure between metal plates. Thus, the Thiokol data would be expected to have larger threshold voltage ratios because of the thinning effect mechanical pressure would have on the propellant samples. The similarity between the ratios of threshold breakdown voltages at one atm to gas pressurized conditions, roughly 2 to 3, for both thin and bulk propellant samples seems logical if no perturbing factor, such as sample thinning, is added.

Thin propellant samples exhibited a lower tendency to sustain burning once electrical breakdown occurred than the bulk propellant samples. This might be caused by increased opportunity for heat losses in electric breakdown zones. Thus, it seems logical to assume that sustained burning might always result from electric breakdowns once propellant masses became large enough.

Rocket motors without electrically conductive motor cases or exterior coatings could have small zones that would be more ESD sensitive than the remainder of the motor structures. These special ESD sensitive sites would probably contain tapered thin propellant grain protrusions and confinement provided by adhesively bonded surfaces. Two examples of ESD sensitized areas are shown in Figure 7. Propellant grain ends terminated with feathery tapered thin propellant projections overlaid by bonded insulation or flame inhibiting rubber would be probable ESD most vulnerable areas. The thin propellant projection would provide enhanced ESD susceptibility versus rounded corners, the bonded rubber covering would add increased ESD vulnerability due to its capability to mechanically confine elevated gas pressures once chemical reaction was started, and the thin propellant connection to bulk propellant would help ensure that sustained burning would occur once an ESD event was initiated. A second sensitive zone could be on the sides of case bonded rocket motor grains where imperfectly installed insulation sheets had small width cracks between them. Again, the enhanced ESD risk factors of thin propellant attached to bulk propellant and mechanical confinement would be obtained.

During production operations stray voltages of 1000 volts are easy to obtain, but with slow deliberate movements during material and equipment transfers triboelectric voltages can be usually controlled to less than 5000 volts. From this point of view manufacturing and field operation ESD safety would be greatly improved if thin propellant projections on motor grains, sharp irregular propellant edges, mechanical confinement, and rapid frictional movements could be avoided or minimized. If such features could be controlled, ESD incidents would be unlikely except with the more ESD sensitive propellants.

Prominent characteristics of HTPB ESD sensitive propellants are high metallic fuel contents, high total solids content, and extremely high electrical resistance. All ESD sensitive propellants that our laboratory has observed contained metallic fuel, usually powdered aluminum metal. How would the factors of metal content, high solids loadings, and extreme electrical resistance act to produce ESD vulnerabilities? Metal fuel particles would provide very high temperatures to aid growth and sustaining of combustion processes. High metal contents and smaller particle sizes would mean that gaps between metal particles would be smaller than otherwise. Smaller metal particles would also mean that particle heat capacities would be small so that high particle temperatures could be readily achieved if high temperatures were developed by ionization processes in binder touching the metal particles. High

solid contents would also reduce gaps between metal particles as compared to lower solid levels. If electric breakdown paths through a metallized propellant jump gaps through binder material between conductive metal particles, the smaller gaps would take lower voltages to traverse the accumulated gaps through the high resistance binder materials. The extraordinary high resistance of the binder would cause the cross section of the path through binder to be very small. Conductive paths through binder probably involves ionized material. Ionizing processes typically involve high temperatures, that are well above the melting point of aluminum oxide films that coat aluminum particles. Melting of aluminum oxide films on aluminum particles has been said to be necessary for efficient aluminum combustion. Once a localized temperature was high enough for aluminum burning, flame propagation without quenching would be probable.

If the initiation scenario above is correct, reduction in the ESD sensitivity of metallized propellants might be accomplished by increasing the cross sectional area of electric breakdown paths through binder material. This would decrease electric breakdown path peak temperature and as a result, the ability to start aluminum burning.

Increasing the electrical conductivity of a solid propellant would spread out an electrical breakdown path. If mobile ions could be introduced into the binder, electrical conductivity would be enhanced. Since HTPB binders are extremely poor ionic solvents, special chemical structures would be required. Large ion salts having low melting points would be expected to be the most soluble.

To test this concept of ESD desensitizing salts tetrabutylammonium tetrabutylboride was put into a KJ-15 propellant formulation at a 0.1% concentration. With the exception that all the aluminum was H-3 (3 micron, Valley Metallurgical) the KJ-15 formulation matches that of the ESD-1 HTPB propellant. The salt was selected because it was the only one at the time in our chemical supplies containing large ion structure. If the boride salt was soluble to an appreciable degree, propellant conductivity would be expected to decline and the ESD vulnerability would also diminish as compared to untreated KJ-15 propellant.

Resistances for 7.6 mm thick by 76 mm diameter discs of both KJ-15 and the boride doped KJ-15 propellants were measured as shown in Table III. A value of 8 times 10 to the 13th power ohms was obtained with the KJ-15 propellant. The salt doped analog propellant gave about 4 times 10 to the 13th power ohms. Although the propellant containing the tetrabutylammonium tetrabutylboride salt was lower in electrical resistance, the change was smaller than expected. This could mean that either the salt wasn't appreciably soluble and/or that the dissolved material didn't have any appreciable free ion concentrations.

ESD testing of the KJ-15 and salt doped analog propellants in the form of 24 mm diameter by 38 mm long cylinders took place at ambient temperatures of about 10 degrees Celsius and one atm. Our ESD test equipment at the time was the model that preceded the one used for the pressure testing. The one atm, minimum threshold breakdown voltage for the KJ-15 propellant was 6 KV as compared to 9 KV for the boride salt doped propellant. Although the increase in threshold breakdown voltage was only 50% of the untreated propellant value, it would probably contribute substantially to ESD safety. This would happen because higher voltages are more difficult to obtain and the greater propellant conductivity would reduce the time that an elevated electric charge on the propellant would take to become dissipated.

Since the upper electrode system had changed from the 25.4 mm diameter propellant sample contact to the 9.5 mm diameter propellant contact, retesting of ESD-1 samples seemed proper to see if changes to the ESD electrical equipment had changed threshold breakdown voltages. With the new upper electrode system minimum breakdown voltage for two ESD-1 24 mm diameter by 38 mm length samples under 10 degree C and 42 atm conditions was 5 and 4 KV. With elevated pressures the ESD-1 propellant samples burned to completion. At ambient pressure two ESD-1 samples had electric breakdowns

at 11 and 12 KV with cracked samples being recovered. These results were greatly different from those obtained earlier with the larger 25.4 mm diameter upper electrode contact. That is, 12 to 15 KV under 40 to 60 atm pressure and 10 C conditions and 18 to 22 KV at ambient pressure. There was no clear explanation on why the two to three fold reduction in threshold breakdown voltages would be caused by an electrode change. Thus, propellant testing after the upper electrode change should be referenced to the ESD-1 propellant threshold voltage values obtained with the same electrode system.

For added soluble salt testing hexadecyltributylphosphonium bromide was purchased. This salt seemed desirable because its melting point was low, 57 C, and its structure contained an even larger ion than the boride salt. An analog to the ESD-1 propellant was made by substituting 0.1% of the phosphonium salt for 0.1% of the HTPB prepolymer in the propellant formulation. This was tested in 24 mm diameter by 38 mm length cylinders at 10 C using the 9.5 mm diameter upper electrode contact as shown in Table III. Two cylindrical samples of the ESD-1 analog propellant containing the hexadecyltributyl phosphonium bromide gave one atm and 10 C breakdown voltages of 26 and 28 KV. Inspection of the analog propellant samples following the test showed no damage for the 26 KV breakdown, indicating electric arcing around the sample; and the 28 KV sample exhibited large cracks and a few missing surface fragments. Since the improvement in minimum breakdown voltage was about twice that obtained for the ESD-1 control samples, these results indicated even better ESD desensitization than by the earlier tetrabutylammonium tetrabutylboride salt.

When the hexadecyltributylphosphonium bromide propellant was tested at 10 C and 42 atm of gaseous nitrogen pressure, a surprising results were obtained. There were threshold electric breakdowns at 5 and 6 KV. This was essentially the same as for ESD-1 propellant control samples tested at the same conditions. Thus, the ESD protective properties of the phosphonium salt seemed essentially to disappear with 40 atm conditions. No explanations for this behavior have been formulated.

4. SUMMARY

Interesting characteristics appeared during examination of aluminized HTPB propellant reactions to high voltage exposures as pressures were varied from one atm to 69 atm (1015 psia). Propellant ESD vulnerability was considerably reduced at one atm pressure as compared to pressures above 30 atm. Thin HTPB propellant (0.64 to 0.69 mm) was found to react at minimum breakdown voltages about one third or less of minimum breakdown voltages for bulk HTPB propellant (38 mm) at one atm pressure. This ratio decreased dramatically at 42 atm pressure where the thin propellant threshold breakdown voltage was roughly one eighth that for the bulk propellant. While the bulk HTPB propellant threshold breakdown voltage decreased in going from one atm to 68 atm, the change was only to about half to one third of the one atm voltage. A similar propellant threshold breakdown voltage ratio was obtained with thin HTPB propellant under gaseous nitrogen pressures. This minimum breakdown voltage ratio for thin HTPB propellant for one atm and 30 to 60 atm pressures, is less than for similar Thiokol data where thinning of the propellant samples under mechanical rather than pneumatic pressure can be used to explain why the Thiokol tests showed greater sensitivity at elevated pressures (Ref. 3). This indicates that bulk propellant, such as in motors, can be relatively safe to ESD conditions since many KVs can be required for ESD initiation with reasonable propellant formulations. However, bulk propellant would be substantially less ESD safe if connected to thin propellant projections in motors. Even sharp corners on propellant probably have some considerable measure of thin propellant ESD characteristics.

Comparisons between mechanically confined between metal plates and gas pressure environments for thin HTPB propellants exhibited much more violent reactions for the case of mechanical confinement. This is likely due to the much greater local pressures around internal breakdown zones because of

the rigidity of the confining structures.

In motors the most ESD vulnerable sites would contain confinement and thin propellant attached to bulk propellant. In these situations confinement ESD sensitization and thin propellant ESD sensitization would be combined with the flame sustainability of the bulk propellant. To minimize motor ESD vulnerability with any given propellant, thin propellant projections and sharp propellant grain corners should be avoided. Since flame inhibitor coatings on the ends of propellant grains would add ESD sensitization through their confining qualities, these also should be avoided, if possible.

Perhaps, the most powerful method of reducing propellant ESD sensitivity would be through careful selection of components going into the propellant formulation. If thrust performance could be slightly compromised, HTPB total solids could be reduced below 88 percent and the aluminum content could be reduced below 20%. The characteristics of the aluminum particles should also be taken into consideration. Spherical aluminum is safest for ESD conditions and the particle sizes should be larger than that used in our ESD-1 propellant (3 and 6 micron).

Introduction of large ion salts has been demonstrated to have beneficial effects upon HTPB propellant ESD vulnerability at one atm but not at 40 atm. Since only about 0.1% of the ionic materials are needed for substantial ESD sensitivity improvements, these materials are a viable way of attaining a measure of propellant and motor ESD resistance.

Since it is very easy to generate 1000 volts or more electric charge during moving operations, propellants and motors should have threshold breakdown voltages much greater than 1000 volts. If a propellant had a minimum breakdown voltage greater than 10,000 volts under low temperature and confinement conditions that might be encountered, it would probably be ESD safe in careful (deliberately slow) moving operations.

5. REFERENCES

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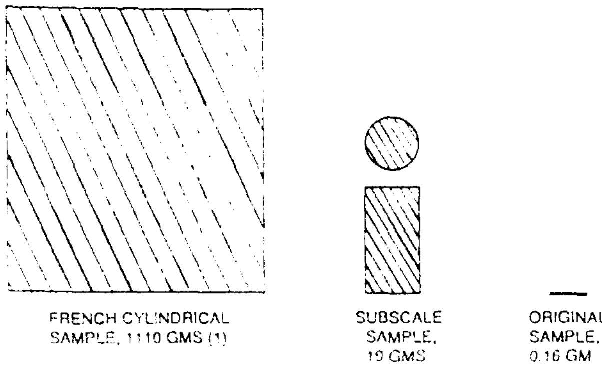
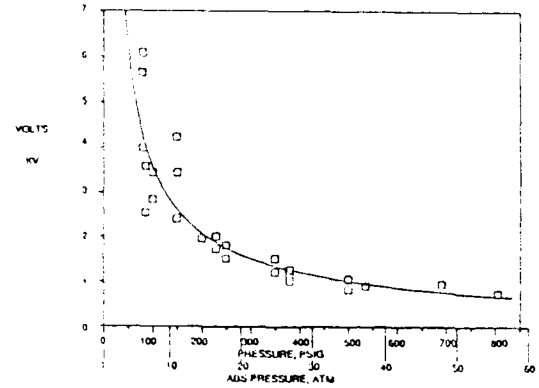
2. Phillip Gibson, Air Force Rocket Propulsion Laboratory, Private Communication.

3. L. E. Davis, Thiokol, Inc., Brigham City, Utah, Private Communication.



1) KENT AND RAT, SNPE, DDESD SEMINAR, 1982

FIGURE 1. ESD PROPELLANT TEST SAMPLE SIZES



L. E. DAVIS, THIOKOL CORP. - PRIVATE COMM.

FIGURE 2. MINIMUM BREAKDOWN VOLTAGE VERSUS PRESSURE, 0.7 MM HTPB

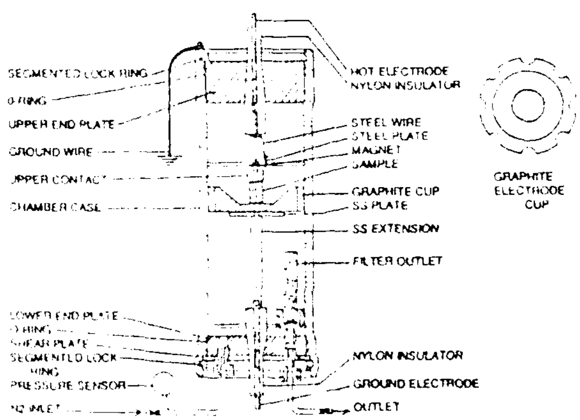


FIGURE 3. PRESSURIZED ESD TEST CHAMBER

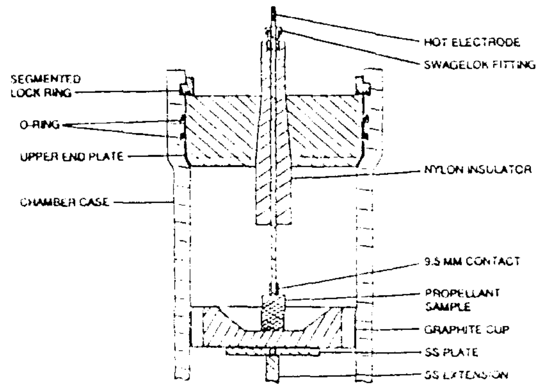


FIGURE 4. ADJUSTABLE UPPER ELECTRODE SYSTEM

TABLE 1. HTPB ESD SENSITIVE FORMULATION

INGREDIENT	%
R-45M, HTPB PREPOLYMER	8.96
DOA, DIOCTYL ADIPATE	2.00
FLEXZONE 6H, N,N'-DIPHENYL PHENYLENEDIAMINE	0.10
DTBH, DITERTIARY BUTYL HYDROQUINONE	0.06
TEPAN, 3M BONDING AGENT	0.10
ODI, OCTADECYL ISOCYANATE	0.04
IPDI, ISOPHORONE DIISOCYANATE	0.74
AL, 3 MICRON, H-3, VALLEY METALLURGICAL	10.00
AL, 6 MICRON, MDX-65, ALCAN	10.00
AP, 200 MICRON AMMONIUM PERCHLORATE	43.00
AP, 10 MICRON AMMONIUM PERCHLORATE	25.00
TOTAL	100.00

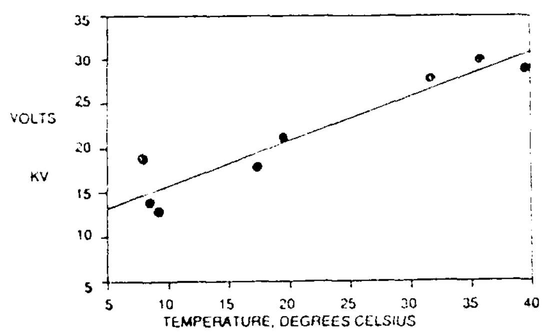


FIGURE 5. MINIMUM BREAKDOWN VOLTAGE VS TEMPERATURE, HTPB BULK PROPELLANT

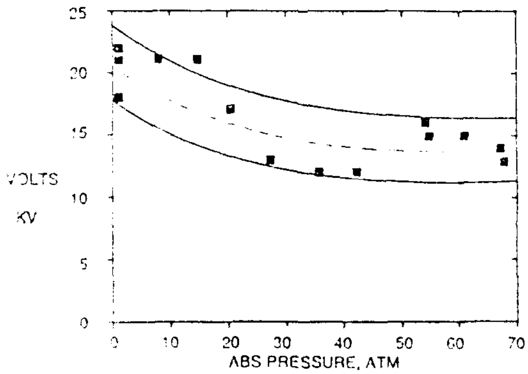


FIGURE 6. THRESHOLD BREAKDOWN VOLTAGE VS PRESSURE, HTPB BULK PROPELL.

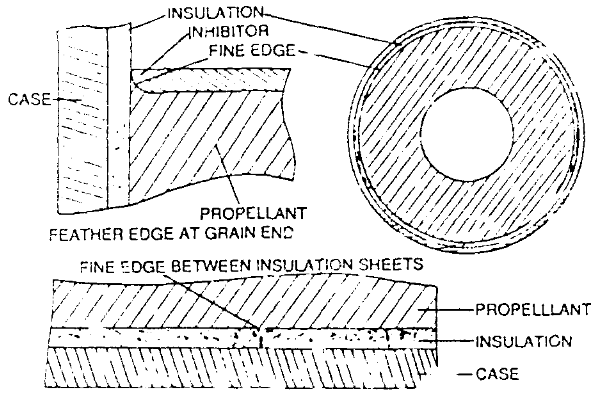


FIGURE 7. PROBAPLE ESD SENSITIVE SITES FOR ROCKET MOTORS

TABLE II. MINIMUM BREAKDOWN VS PRESSURE FOR THIN ESD-1 SAMPLES

THICKNESSES - 0.64 TO 0.69 MM   TEMPERATURE - 10 C

0.5 MM DIAMETER ELECTRODE

PROPELLANT	PRESSURE, ATM	VOLTS, KV
ESD-1, THIN	1	1.4
ESD-1, THIN	1	1.4
ESD-1, THIN	37	0.7
ESD-1, THIN	40	0.5

TABLE III. ESD DESENSITIZING SALTS

TEMPERATURE, 10 C.   9.5 MM DIAMETER ELECTRODE

PROPELLANT	RESISTANCE OHMS	PRESSURE ATM	MINIMUM BREAKDOWN VOLTAGE, KV
KJ-15 (HTPB/H-3)	8×10^{13}	1	6
ANALOG (HTPB/H-3/0.1% TETRABUTYLAMMONIUM TETRABUTYLBORIDE)	4×10^{13}	1	9
ESD-1 (HTPB/3&6 MICRON)	------	1	11
ESD-1	------	42	4
ANALOG (HTPB/3&6 MICRON/ 0.1% HEXADECYLTRIBUTYL-PHOSPHONIUM BROMIDE)	------	1	26
ANALOG	------	42	5

- MODERATE ESD HAZARD INCREASE WITH ELEVATED PRESSURES
- GREATER ESD SENSITIVITY WITH PRESSURIZATION AND THIN PROPELLANT
- MECHANICAL CONFINEMENT GIVES STRONGER REACTION
- MOTOR ESD SAFETY AVOIDS THIN PROJECTIONS
- ESD VULNERABILITY PARTIALLY REDUCED BY LARGE ION SALTS

FIGURE 8. SUMMARY, ESD TRAITS UNDER PRESSURE

Discussion

QUESTION BY COLE, CANADA: Did they investigate various concentrations of ion salts and attempt to find a optimum level?

ANSWER: They did try 1% of ion salt but it seemed to interfere with propellant cure since it resulted in soft propellant. However, this propellant did seem to have reduced ESD sensitivity. Samples with .01% of ion salt were also produced but not tested.

QUESTION BY MAWBEY, UK: I believe that SNPE found that multiple discharges would progressively degrade the material so that although ignition did not occur on the first discharge later events would cause ignition. Have you found a similar behavior?

ANSWER: In our test procedure we typically treat the propellant sample with ten pulses (voltage applications) at each voltage level or stop when electric breakdown occurs. If no sample response occurs with ten pulses, the voltage is incrementally raised until propellant reaction occurs. It is very common that no sample response occurs on the first pulse, but at some later voltage application at the same voltage level. That is why we conduct pulses at each voltage as we proceed with the testing. If you start with a subsequent sample with an initial voltage 15% above that providing electric breakdown with an earlier sample, you get predominantly breakdown on the first voltage application, but not always.

QUESTION BY COUTURIER, FRANCE?: The present results show a great sensitivity to temperature. The greater risk therefore seems to be during manipulations when the weather is dry and cold. Have tests with negative temperatures been done? What are the results?

ANSWER: Since someone else had determined lower temperature influence on HTPB propellant ESD breakdown, we were only interested in the temperature range of interest with our experiments and our particular propellant. It is clear that if temperatures were further reduced that threshold or minimum breakdown voltages for the HTPB propellant would have continued to decline. So far, we have only completed a limited amount of work with the ESD characteristics associated with the large ion salt additives. Investigation of breakdown voltages of the large ion salt added propellants to lower temperatures at one atmosphere might be interesting.

Development of a Minimum Smoke Propellant Based on Glycidyl Azide Polymer and Ammonium Nitrate

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SUMMARY

Composite rocket propellants traditionally developed and produced in Canada are based primarily on ammonium perchlorate (AP) dispersed in a polybutadiene (HTPB) binder. Depending on the atmospheric conditions, such propellants can produce a significant amount of secondary smoke which is undesirable for certain applications. To overcome this problem, the Defense Research Establishment Valcartier (DREV) has initiated the development of a minimum smoke, low vulnerability propellant. The new propellant uses ammonium nitrate (AN) as the oxidizer and glycidyl azide polymer (GAP) as the energetic binder. The efforts made and the characteristics of a baseline minimum smoke formulation are described. This formulation meets minimum criteria for processing safety, chemical stability and mechanical integrity. It falls short of the performance of an AP/HTPB propellant. Means of improving the performance are described.

1. INTRODUCTION

All existing high-energy propellants used in solid rocket motors are deficient in at least one of two aspects: signature or detonability. Conventional composite propellants using ammonium perchlorate as the oxidizer are non-detonable under normal conditions but generate large amounts of hydrogen chloride, a corrosive and toxic gas that contributes to the formation of secondary smoke under certain frequent atmospheric conditions. Furthermore, current high-energy minimum-smoke propellants contain large quantities of nitramine explosive that makes them detonable in tactical missile configurations.

One approach to resolve this dilemma is to develop a composite formulation in which most or all of the ammonium perchlorate is replaced by phase-stabilized ammonium nitrate (PSAN). Unfortunately, ammonium nitrate is not as oxygen-rich or as dense as ammonium perchlorate. To regain the lost energy, it is therefore necessary to replace the inert binder, typically a urethane cross-linked polybutadiene in the AP propellant, by an energetic one. In this context, a binder based on a mixture of a glycidyl azide polymer (GAP) and one or more commercially available nitroplasticizers is receiving a great deal of attention, the goal being to produce a GAP/PSAN/nitroplasticizer propellant that approaches a conventional polybutadiene/ammonium perchlorate propellant in terms of structural integrity, energy density, stability, sensitivity and burning rate flexibility.

This paper discusses the progress made at the Defence Research Establishment, Valcartier to develop such a propellant. Specifically, the characteristics of a baseline, minimum smoke formulation, which meets minimum criteria for processing safety, chemical stability and mechanical integrity, are described. This baseline formulation falls short of the performance of an AP/HTPB propellant. Means of improving the performance are then described.

2. REQUIREMENTS

2.1 Essential

The essential requirements for the baseline propellant were:

a. processing risk no greater than conventional reduced smoke composite propellant. Quantitatively this means impact and friction sensitivity values for the uncured formulation , as measured on BAM testing apparatuses, equal or greater than 15 J and 30 N respectively.

b. processability, i.e. reasonable end-of-mix viscosity, curing time and the absence of sedimentation during cure.

c. chemical stability: defined as no more than 2 ml/g of gas evolution when subjected to a vacuum stability test (VST) at 100°C for 48 hours.

d. room temperature mechanical properties adequate to cast simple test motors.

2.1 Desirable

The ultimate goal is to have a formulation with energy, density, structural integrity and burning characteristics equivalent or superior to a reduced smoke composite propellant. These values can be quantified as follows:

a. a specific impulse value (I_{SP}) of 240 seconds.

b. a density of at least 1.6 g/ml.

c. structural integrity: at - 54°C, elongation at maximum strength greater than 25% and a maximum strength at room temperature greater than 0.6 MPa.

3. PRELIMINARY STUDIES

Prior to formulating a complete propellant system, numerous studies were conducted to assess various potential ingredients from the points of view of energy, stability and compatibility and sensitivity. As well an exhaustive series of tests was conducted to optimise the binder system (e.g. without oxidizer).

3.1 Ingredients

The PSAN was procured from the Hercules Aerospace Company of McGregor, Texas. The polymer used was commercial glycidyl azide polymer called GAP obtained from Rocketdyne, Canoga Park, California. The plasticizers tested were diethylene glycol dinitrate (DEGDN), triethylene glycol dinitrate (TEGDN), trimethylene glycol trinitrate (TMETN) and butanetriol trinitrate (BTTN), all were obtained from Trojan Corporation of Spanish Fork, Utah. A 50/50 mixture of bis-dinitropropyl acetal and bis-dinitropropyl formal (BDNPA/F) obtained from Aerojet Limited of Sacramento, California was also evaluated. The isocyanates were N-100 from Bayer Canada Inc. in Montréal, Québec and isophorone diisocyanate (IPDI) from Huels Corp. in New York, New York. The stabilizers such as diphenylamine (DPA) and methylnitroaniline (MNA) were procured from BDH Inc. in Montréal, Québec. In some cases di-butyltin dilaurate (DBTDL), from Aldrich Chemical, Milwaukee, Wisconsin was used as a curing catalyst.

3.2 Ballistic Performances

The theoretical performance of several formulations comprising GAP, ammonium nitrate and one energetic plasticizer were determined. Using a thermochemical code, the theoretical specific impulse (I_{SP}) of each propellant system was calculated as a function of the relative quantity of its three components. In this way, triangular composition-performance diagrams were developed for each propellant system considered, an example of which is shown in Fig.1 for a composition including TMETN as the plasticizer and some HMX (10%) as a secondary oxidizer. The equivalence ratio ϕ is defined as the ratio of the total number of reducing valences to the total number of oxidizing valences per unit mass of propellant. Results show that if the oxidizer charge consist solely of ammonium nitrate, specific impulses comparable to those of a conventional AP/HTPB propellant can only be achieved at plasticizer/polymer ratios of greater than 1/1. Such high values are necessary because ammonium nitrate (AN) is a relatively poor oxidizer. Such a heavily plasticised binder may be advantageous from a processing point of view, ... the mechanical properties and vulnerability of the p...ant will likely be adversely affected.

3.3 Stability/Compatibility Studies

The method used to evaluate the stability/compatibility of ingredients and mixtures was described elsewhere (Ref. 1). Testing is performed in a modified mercury-free vacuum

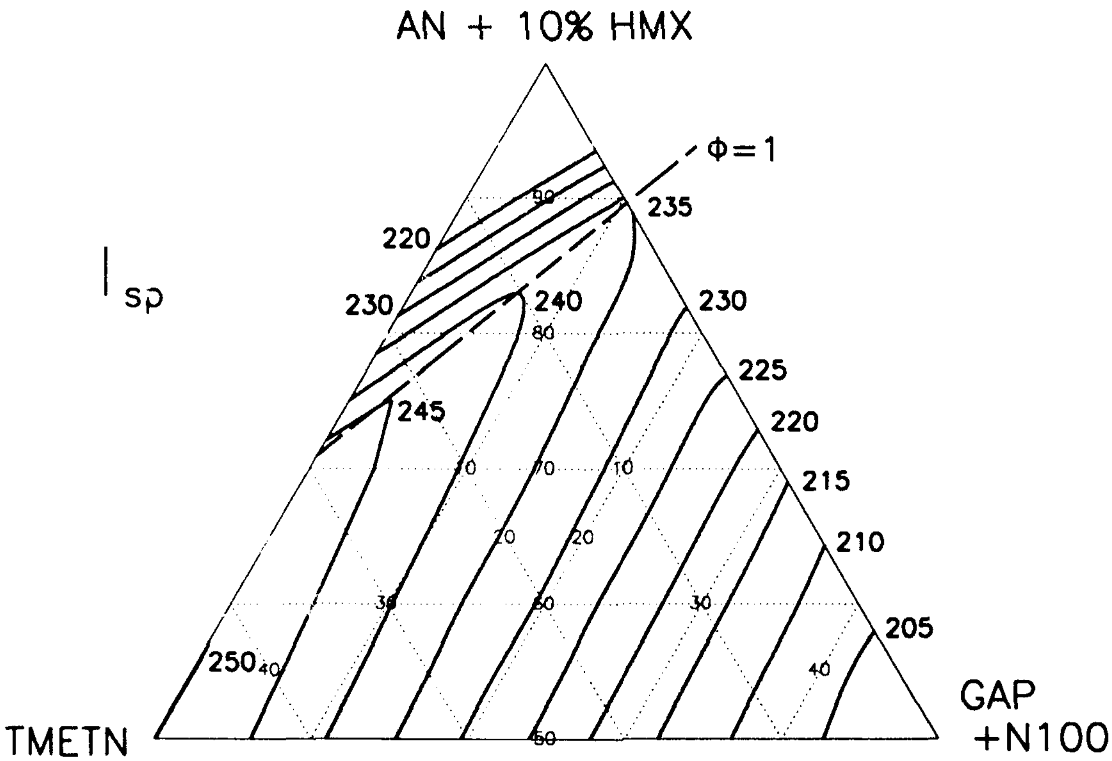

Figure 1

Composition-Performance Diagram

stability cell for 48 hours at 100°C. Gases produced are analyzed using a gas chromatograph.

Results were first obtained for GAP, plasticizers and mixtures of them. The BDNPA/F proved to be the most stable plasticizer, the more energetic TMETN and BTTN unfortunately being less stable. Further testing revealed major incompatibilities between AN and both GAP and BDNPA/F as illustrated below.

Table 1
Incompatibility in GAP/AN/BDNPA/F Mixtures

SAMPLE	GAS VOLUME ml/g
GAP	0.2
AN	0.1
BDNPA/F	0.2
GAP/BDNPA/F	0.8
GAP/AN	6.0
BDNPA/F/AN	4.6

Fortunately, effective chemical stabilizers, such as DPA and MNA, were found to keep the gas evolution within acceptable limits, as shown in Table 2.

3.4 Sensitivity Studies
All ingredients were tested for impact and friction sensitivity on BAM testing apparatuses using standard methods. Autoignition temperature were evaluated using a DREV developed furnace. Results revealed that the nitrated esters are by far the most sensitive to impact, with BDNPA/F being the least sensitive of the plasticizers.

Small propellant batches (25 g) were prepared in a remotely controlled simple glass vial and stirrer arrangement and tested for impact, friction sensitivity and autoignition temperature. Later, 100 g batches were prepared in an Atlantic Research 2 CV Helicone Mixer for further evaluation. As shown in Table 3, the sample of GAP/PSAN/TMETN uncured mixture proved to be very sensitive to impact when compared with the AP/HTPB propellant. It was found that BDNPA/F produced the least sensitive propellant paste in terms of friction sensitivity.

3.5 Oxidizer Studies
On the basis of its availability and good phase stability, nickel oxide phase stabilized ammonium nitrate (PSAN), containing 3.5% NiO, was selected after a study of available materials and a review of ICT's work (Ref. 2). In the initial propellant processing experiments, the PSAN was not dry

Table 2
Chemical Stability of GAP/N-100/BDNPA/F/AN Mixtures

SAMPLE	GAS VOLUME ml/g	GAS COMPOSITION (%)			
		CO	CO_2	N_2	N_2O
GAP/N-100/BDNPA/F	0.6	0	35	60	5
GAP/N-100/BDNPA/F/AN	9.0	1	24	55	20
GAP/N-100/BDNPA/F/AN +2% MNA	0.5	0	44	53	2

Table 3
Sensitivity of Uncured Propellant

SAMPLE	IMPACT Joules	FRICTION Newtons	AUTOIGNITION TEMPERATURE °C
AP/HTPB	15-25	30	245
PSAN/GAP/TMETN	<1.5	192	160
PSAN/GAP/BDNPA/F	15-25	>360	203

nor pre-treated prior to use, although care was taken to minimize exposure to moisture during manipulation. Discrepancies in the results obtained suggested that control of the moisture content of PSAN could have a large influence on the curing of the propellant. A reliable method for determining the water content of NiO PSAN was developed and experimented (Ref. 3), allowing assessment of different drying methods and control of the PSAN water content. The PSAN, as received, shows an average particle size of 190 μm and a fairly wide distribution as determined using a Malvern Particle Sizer.

3.6 Binder studies

Various binder systems were studied by evaluating the effects of ingredients variation (polymers, curing agents, plasticizers, catalysts) on the strength and strain capabilities of the resulting binder. The results of the study demonstrated that it was possible to formulate binders having mechanical properties that approach the room-temperature values for the current inert plasticized HTPB binder, the elongation being higher, 800 vs 600-700% and the strength being lower, 0.06-0.1 vs 0.2 MPa, in the case of plasticized GAP-based binders cured with IPDI. Unplasticized GAP binders showed superior strength values (0.25-0.35 MPa). Systems with a polymer/plasticizer ratio greater than one are more difficult to cure and generally shows inferior properties.

Early experiments showed that, in a propellant, curing would not occur with IPDI alone. So binders cured with a mixture of IPDI and N-100 were prepared and studied both in plasticized and unplasticized form. The observed tendency was the same for both systems; a very sharp decrease in the elongation values, from 800 to 100%, as the N-100 content increased, while the stress values did not vary very much, ranging between 0.05 and 0.06 MPa. The use of N-100 as the sole curing agent resulted in harder, less flexible binders than IPDI-based binders.

4. BASELINE PROPELLANT

4.1 Formulation

A baseline formulation was established by combining the best ingredients available from the point of view of sensitivity, stability, mechanical properties and energy. Thus the binder selected was based on GAP cured by a mixture of IPDI and N-100. The system was plasticised with BDNPA/F, in a polymer/plasticizer ratio of 1/1, specifically for its low sensitivity and good stability. In some cases, DBTDL at very low concentration was used as a curing rate catalyst. The oxidizer consisted of 70% by weight of PSAN containing 3.5% NiO. The formulation also included 2% by weight of DPA as a chemical stabilizer.

4.2 Mechanical Properties

The mechanical properties were determined using an Instron apparatus at a crosshead speed of 50 mm/min using standard JANAF dogbones. The results are given in Table 4, where ε_m and ε_r are elongation values at respectively maximum and rupture strength, while σ_m and σ_r are respectively maximum and rupture tensile strength values, E being the modulus. The uncatalysed system showed room temperature properties that were close to those of an aluminised AP/HTPB propellant containing no bonding agents (Ref. 4). The properties at - 40°C were not very good, which is not surprising in view of the relatively poor glass transition temperature of GAP, thus elongation was very low and strength very high. Lower properties were obtained with the catalysed binder.

4.3 Processing

The baseline formulation, when prepared in an Atlantic Research 8 CV Helicone Mixer at a batch size of 10 kg, demonstrated good processability with end-of-mix viscosities between 4 and 5 kP and pot-lives in the 3 to 4 hours range. Although flowability was not as good as a standard

Table 4
Mechanical Properties

SAMPLE	TEMPERATURE °C	ε_m %	ε_r %	σ_m MPa	σ_r MPa	E MPa
Baseline	60	14.1	17.7	0.26	0.23	3.22
	23	16.8	31.9	0.28	0.23	4.13
	-40	3.9	7.8	4.99	4.1	267
Baseline *(with cure catalyst)*	60	11.5	14.3	0.25	0.22	3.34
	23	13.5	25.7	0.26	0.21	3.97
	-40	3.5	7.6	5.23	4.22	313
AP/Al/HTPB *(no bonding agents)* from Ref. 4	23	16.5		0.37		4.59

AP/HTPB propellant, the baseline formulation was nevertheless castable.

4.4 Ballistic

The baseline formulation has a theoretical specific impulse (I_{SP}) of 222 seconds, evaluated using the thermochemical code. Burning rate measurements were performed in a strand burner at an initial propellant temperature of 21°C and three different pressure levels (6.89, 13.76 and 20.67 MPa). Results were correlated using the De Vielle burning rate law. For both the catalysed and uncatalysed baseline propellant formulations, a burning rate of 5.2 mm/s at 6.89 Mpa and an exponent of 0.63 were measured.

4.5 Stability

VST results of actual propellants gave a value of 17 ml of gas produced per gram of propellant for a formulation containing no stabilizer compared to 3.6 ml/g for one including two percent by weight of MNA and 1.6 ml/g for the baseline formulation that used DPA.

5. DISCUSSION

5.1 Deficiencies

The main deficiencies of the baseline formulation are a low I_{SP}, a strength of about a third the desired value, poor mechanical properties at low temperature, low burning rate and high pressure exponent. Castability would benefit from an improvement in the flowability of the propellant.

5.2 Improvements

The goal was then to improve the baseline formulation in order to bring its performances closer to the requirements set forth at the beginning of this project. To realise this objective, the baseline formulation was used to study the effect of the inclusion of different additives such as burning rate catalysts, bonding agents, stabilizers and plasticizers on the mechanical and ballistic properties, the stability and the sensitivity.

To improve the low temperature mechanical properties, it is necessary to lower the glass transition temperature of the binder. Work in progress at DREV has already demonstrated that the replacement of a fraction of the BDNPA/F by TEGDN, at the cost of some energy, could provide improved low temperature properties while maintaining sensitivity within acceptable limits. Inclusion of the more energetic plasticizers TMETN or BTTN did not provide much improvement in low temperature properties and was detrimental to sensitivity.

The work of Perreault and Duchesne (Ref. 4) on aluminised AP/HTPB propellant has demonstrated the drastic improvement obtainable by the judicious use of a combination of bonding agents and it is believed that the identification of suitable bonding agents for the PSAN/GAP system is of primary importance for obtaining adequate mechanical properties. Already work is in progress and suitable bonding agents, improving the strength and showing a positive effect on the stability, have been identified.

The addition of a catalyst will be necessary to control the rate of burning and lower the pressure exponent. A number of potential candidates were screened and effective burning rate modifiers have been identified.

Small test motors have been filled with a modified formulation (i.e. including a ballistic modifier) and were successfully fired. Such a formulation is presently being transferred to the industry for further development work.

6. CONCLUDING REMARKS

We have succeeded in formulating a baseline propellant that meets some of the requirements but not all. The new propellant uses phase stabilized ammonium nitrate (PSAN) as the oxidizer, glycidyl azide polymer (GAP) as the energetic binder, and bis-dinitropropyl acetal/formal (BDNPA/F) as the plasticizer. This formulation meets minimum criteria for processing safety, chemical stability, processability and shows enough mechanical integrity to allow casting of simple propellant grains. However, the formulation falls short of the performance of the AP/HTPB propellant but work is going on to improve it.

7. ACKNOWLEDGEMENTS

The authors would like to thank the members of the Process Engineering Group for their dedicated support and Mr. D.L. Smith for his stimulating contribution.

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Discussion

QUESTION BY BOGGS, US: In one of your slides you showed that you were using phase stabilized ammonium nitrate (PSAN) having 3.5% NiO. Currently some people in the US are being told that they cannot use PSAN having NiO. Are there any such restrictions in Canada on use of NiO PSAN?

ANSWER: At this point is time, there is no formal restriction imposed on us. We are presently in the process of procuring NiO PSAN for continuing our work and the matter of the carcinogenicity of NiO was raised by our own Supply Department upon reception of the new Safety Data sheet. There is a possibility that the people responsible for environmental questions might have their word to say but it seems likely that we will be allowed to procure small quantities for R&D purposes. We are aware of the situation in the US and are looking foi potential candidates to replace NiO PSAN.

QUESTION BY WHITEHOUSE, UK: The low level and restricted range of burning rate for AN propellants will pose problems for rocket motor designers. What do you consider the potential for improvements to be?

ANSWER: The baseline formulation does not include a burning rate catalyst. The modified formulation including a ballistic modifier shows a burning rate of 8 mm/s at 6.89 MPa and a pressure exponent of around .5 in the pressure range of 6.89 - 27.56 MPa (1000 - 4000 psi). The inclusion of finer particle size oxidizer might help increase the burning rate even further.

QUESTION BY MENKE, FRG: What might be the reason for the high impact sensitivity of the PSAN/GAP/TMETN sample?

ANSWER: Our experience demonstrates that the TMETN/PSAN combination is the source of the problem. In fact it seems that any combination of AN (or AP for that matter) with nitrated esters will result in an increased impact sensitivity. It is reproducible.

QUESTION BY MENKE, FRG: Which choices do you use for getting a better performance of the smokeless AN/GAP propellant, if BDNPF/A must be replaced and sensitivity should not increase?

ANSWER: Experience have shown that up to 30% of the BDNPF/A can be replaced by TMETN or BTTN while maintaining the impact sensitivity at the same level observed for the uncured AP/HTPB propellant. This of course, would result in a slight improvement in performance. Increasing the solids loading is another option. An Isp of 230 seconds might be reachable through careful optimization but this is probably the maximum that can be obtained without jeopardizing the low sensitivity and/or low smokelessness of the formulation.

THE DESIGN FEATURES OF ROCKET MOTORS RELATING TO INSENSITIVE MUNITION RESPONSE TO THERMO-MECHANICAL STIMULI

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Summary

Since the late 1970's Royal Ordnance Rocket Motors Division has conducted Insensitive Munitions trials on approximately 500 solid propellant rocket motors and data from over 400 of these have been included in a recently structured database. These trials preceded the current standards of MIL-STD-2105 and OB Proc 42657 and as a result most of these trials were conducted on an individual basis in order to understand the basic reponses to a wide range of threats. Although the trials were not undertaken as a balanced series of experiments analysis of the data does permit some useful observation and comparisons to be made. In particular the results of 0.5 inch bullet impact trials and fuel fire (Fast Cook-off) tests are considered to be particularly relevant to the current UK, NATO and USA requirements and these are discussed in detail.

The general conclusions from these trials emphasise the importance of both the propellant type and body structure in the response to either mechanical or thermal attack. The database has enabled the capability of desiging solid propellant rocket motors to meet bullect impact and fuel fire requirements

List of Abbreviations

AL	Aluminium Alloy
BI	Bullet Impact
CB	Case Bonded
CDB	Cast Double Base
CF	Carbon Fibre Composite
CL	Cartridge Loaded
CMCDB	Composite Modified Cast Double Base
EMCDB	Elastomer Modified Cast Double Base
FCO	Fast Cook-Off
HTPB	Hydroxyl Terminated Polybutadiene
IM	Insensitive Munitions
KOA	Kevlar Overwrapped Aluminium
MOD	Ministry of Defence
P&EE	Proof and Experimental Establishment
RDX	Nitramine (used as a propellant filler)
RO	Royal Ordnance
RMD	Rocket Motors Division
SCO	Slow Cook-Off
SD	Sympathetic Detonation
SSL	Steel Strip Laminate
UK	United Kingdom

1 Introduction

As an aid to developing an understanding of the likely response of a particular rocket motor to an external stimulus, such as a bullet impact or a fuel fire, a large number of IM trials has been undertaken by the Rocket Motors Division of Royal Ordnance. The range facilities used for most of these trails were under the control of the UK MOD, with the majority being conducted at P&EE Pendine.

Approximately 500 rocket motors have been consumed in these IM trials and data from over 400 of these have been compiled onto a recently structured IM database. In these trials the effects of projectile impact, detonating shells, sympathetic detonation, fuel fires and torch flames have been assessed against various combinations of case structure, propellant types and grain configurations. Testing began in the late 1970's and continues to day with trials to explore the reaction of motors to the newly defined requirements of MIL-STD-2105 and OB Proc 42657.

Although all of the data contained on the database are of value the trials were generally conducted on an individual basis and were not undertaken as a balanced series of experiments. The sample size of some data sets are at present too small to support diffinitive conclusions and in others the trial configurations employed differ from the current requirements of MIL-STD-2105 and OB Proc 42657 and may therefore be of limited interest. This paper is thus confined to giving an outline summary of the IM database with detailed analysis being restricted to the results of the 167 half inch bullet impact tests and the 36 fuel fire (Fast cook-off) trials.

Over half of the trials on the IM database were conducted against motors using steel strip laminate cases as this system was perceived at an early stage of its development to have the ability to attenuate violent reactions: for those unfamiliar with this method of case construction further information is given in Annex A.

2 RO IM Database

Since the late 1970's RO RMD has carried out IM trials on over 500 rocket motors. Some of this work was carried out under research funding, and some was project funded. In the former the aims were generally to investigate the reactions of a wi e range of motor types to a variety of stimuli, whereas in the latter the interest was more specific, usually to comply with technical requirements.

To aid with analysis and interpretation the data from these trials are now being added to a computer database. At the same time the opportunity has been taken to re-classify the results in line with the current MIL-STD-2105 definitions, ie, 1 Detonation, 2 Partial Detonation, 3 Explosion, 4 Deflagration, 5 Burning and 6 Propulsion. To date the results of trials carried out on over 400 motors have been compiled. When completed it is believed that the database will help identify trends, suggest areas for further study, highlight gaps in the data, and eliminate unnecessary replication in future trials.

Many of the IM trials conducted by RO RMD were carried out before the advent of MIL-STD-2105 and OB Proc 42657 and followed guidelines developed by RMD. Projectile impact trials have been carried out with a variety of bullet types and the effect of blast and fragment impact has been simulated by detonating 105 mm shells in close

proximity to test motors. Sympathetic detonation experiments have been conducted by placing a detonator and explosive in the conduit of donor motors. The effects of temperature have also been examined by repeating trials on hot and cold conditioned motors. Motors with and without external insulation have been subjected to fuel fires in large and small hearths and the influence of rig design on motor reactions has also been assessed.

The results of these trials are summarised in Tables 1 to 18. The following Table gives details on the database composition as well as a flavour of the wealth of information already compiled, a conservative estimate of the cost of repeating these trials in 1991 would be around £10M.

Composition of the RO RMD IM Database Summary

Total	Number of Motors
Case Construction	443
Steel Strip Laminate	243
Steel	157
Kevlar Overwound Aluminium	17
Carbon Fibre	15
Aluminium	11
Propellant	
CDB	330
EMCDB	58
CMCDB	9
HTPB	13
Extruded Cordite	33
Grain Loading	
Case Bonded	296
Cartridge Loaded	147
Method of Attack	
0.5 inch Bullet Single Shot	154
0.5 inch Bullet Automatic Fire	13
7.62 mm Bullet	26
20 mm Bullet	38
[illegible].3 mm Ball	9
[illegible].0 mm Ball	5
Fragments	17
Detonating Donors	141
Fire	40
Temperature	
Below 0°C	69
0 - 20°C	350
Above 20°C	24

Fortunately the procedures used for bullet impact and fuel fire (Fast cook-off) trials are similar to those required by MIL-STD-2104 and OB Proc 42657, hence the considerable data gathered from the 0.5 inch bullet impact and the fuel fire tests are relevant to these. More details on the results obtained from these tests are given in Sections 3 and 4 respectively.

3 0.5 inch Bullet Impact Trials

A total of 154, single shot, 0.5 inch bullet impact trials (as OB Proc 42657) are included in the database. In addition information on 4 trials conducted with the simultaneous strike of two 0.5 inch bullets and 9 using the automatic fire of three 0.5 inch rounds (as MIL-STD 2105) is also included. The data from these trials are summarised in Tables 1 to 3. Details of the BI test procedure are given in Annex B.

3.1 Single 0.5 inch Bullet

Trials have been conducted against SSL, Steel, KOA, CF and Al cases. The propellants tested are Cordite, HTPB, CMCDB, CDB and EMCDB the latter two with and without RDX. Motors have been tested at conditioned temperatures of -50, -40, -30, -20, 0 and +60°C.

In general these trials were conducted to examine the reactions of various combinations of propellant and case construction. The objective of the trials being to provide an indication of the IM performance of specific case types and propellants together with an assessment of the effects of temperature.

The majority of motors used in these trials were taken from production and development programmes and were not specifically built for IM research. Hence the trials carried out do not follow an experimental design and a number of gaps in the test matrix shown in Table 1 will be apparent. However, despite this limitation the results obtained do permit some useful observations and comparisons to be made and may be used to indicate direction for future studies.

3.1.1 Motor Temperature Effects

Regardless of the type of propellant or case material the adverse effect of very low temperatures is clearly apparent in the data. At the temperature of -50°C the effects of case and propellant type are second order. Of the seven trials carried out at this temperature all produced reactions more severe than burning, ie six explosions and one detonation. Statistical analysis, based on the assumption that different propellants have no effect on the pass/failure probability, indicates that the general probability of failure at -50°C is 0.91 with 50% confidence. This is no doubt due to the brittle nature of all propellants at such low temperatures.

3.1.2 Propellant Classification

The propellants represented in the IM database have been classified using the US card gap definition as either Class 1.1 or Class 1.3. All of the HTPB charges are Class 1.3, as are the CDB and EMCDB propellants which do not contain either refractories, aluminium or nitramine fillers. The CDB and EMCDB propellants containing refractory, aluminium or nitramine fillers give card gap values in excess of 70 and are therefore Class 1.1 by the US definition. However, they are all 1.3C by NATO standards. The results of the 0.5 inch bullet impact trials have been segregated by USA propellant classification as shown in Tables 1a and 1b.

The trials conducted on the HTPB and EMCDB motors allow an assessment to be made of the value of the propellant classification as a means of predicting an IM reaction.

For a given case construction trials across the temperature range of -50°C to +60°C trials have been carried out on both of these propellant types. From these results it can be seen that the IM reactions of the Class 1.3, HTPB propellant and the Class 1.1, EMCDB propellant are virtually identical. It should be noted, however, that all of the case types represented in this sample are of a laminate type structure and caution should be exercised in relating these results to homogenous cases.

3.1.3 Charge Configuration Effect

From an initial glance at Table 1 it might be thought that an indication of the significance of whether a charge is cartridge loaded or case bonded could be obtained from the results of the CDB motor trials, the sample size of the CDB/RDX and EMCDB motors being too small to justify analysis. By restricting analysis to the steel cased motor trials the effects of temperature can also be filtered out as these were all conducted at ambient. Of the 43 trials carried out on cartridge loaded motors 58% failed whereas 79% of the case bonded motors failed. Unfortunately different class propellants were used in these trials and this may also have influenced the results. The propellant used in all 43 cartridge loaded charges was Class 1.3 whereas only 2 of the 14 case bonded charges used Class 1.3 propellant. It is tempting on the basis of the HTPB/EMCDB comparison given in Section 3.1.2 to assume that the class of propellant makes little difference. However, there may be a case/propellant interaction, which it is not possible to test with the available data, which would invalidate such an assumption, hence no clear indication of the effect of charge configuration upon BI reaction can be drawn.

3.1.4 Case and Propellant Effects

To assess the possible influence of the case and propellant type upon the reactions witnessed it is necessary, to filter out the charge configuration and temperature effects. Ideally this would be achieved by comparing only those results obtained for identical configurations and temperatures. Unfortunately the sample size for any given temperature across all case types is too small to make this practical.

However, by considering just the HTPB and the CDB Class 1.1 case bonded propellant motors, reducing temperature effects by ignoring those tests conducted below -30°C and pooling all trials conducted at temperatures of -30°C and above it is possible to make some initial comparisons between case and propellant types. The data of Table 1 has been simplified, on this basis as shown in Table 18. The results are classified as either P or F, ie., respectively, a reaction no more severe, pass, or more severe, fail, than burning.

Analysing the data in Table 18, row and column wise, gives an indication of relative BI performance of the various case constructions and propellant types. For example looking at the HTPB column shows SSL gave 2 pass results and 0 fail results, compared to 2 failures and 0 passes for KOA and 1 failure and 1 pass for CF. Similarly examining the KOA row shows that HTPB gave 2 failures and 0 passes, EMCDB, 2 passes and 0 failures, CDB 2 passes and 1 failure and CDB/RDX 1 failure and 0 passes.

A further insight into the propellant/case combination can be gained from a statistical analysis of the ambient trials conducted on EMCDBRDX/SSL, CDB CL/SSL, CDB CL/Al, CDB CB/SSL, CDB CB/steel and C/steel. It can be concluded from the total number of passes and failures from this group of trials that an overall probability of failure of 0.5 is not unreasonable. For the null hypothesis, HO, of equal likelihood of pass or failure, and the test statistic is the probability of this outcome given HO is true. These data and test statistics are as follows:-

	Pass	Fail	Total	Test Statistic
EMCDBRDX/ SSL	7	0	7	0.008
CDB CL/ Steel	18	25	43	0.12
CDB CL/Al	11	0	11	0.0005
CDB CB/SSL	16	0	16	0.00002
CDB CB/ Steel	3	11	14	0.029
C/Steel	5	17	22	0.008
Total	60	53	113	

By rejecting the null hypothesis if the test statistic is less than 0.05 it can be seen that only one propellant/case combination has given results consistent with an equal likelihood of pass/failure, ie CDB CL/Steel. Otherwise all the above combinations using a steel body gave a larger than expected number of failures and correspondingly the other bodies, SSL and Al, had statistically fewer failures.

Pooling ambient trials across propellant types gives the following probabilities of failure for the SSL, Al and steel cased motors:-

	SSL	Al	Steel
95% Confidence	p <0.12	<0.24	<0.76

3.1.5 Rig Effects

All of the 0.5 inch bullet impact trials included in the database to date were conducted following the procedures described in Annex B. The rig design employed on these trials holds the motor by retaining both ends in Vee's with loose fittings top clamps.

During discussions with Naval Weapons Centre, China Lake, doubts on the possible influence of rig design on the motor reaction were voiced. To address these concerns five EMCDBRDX/SSL motors were subjected to 0.5 inch and 20mm bullet impact trials. In these tests the rig used was a copy of the NWC 'A' frame rig in which the motors are supported in a simulated air carriage configuration using two launch hangers, the ends are free. All of the motors used in these trials gave reaction typical of this motor, ie. no more severe than burning.

3.2 Multiple 0.5 inch BI Trials

The multiple, impact trials carried out are limited to two case types and three propellants, also the number of tests conducted is insufficient to support statistical analysis. However, because of the similarity of these trials to the current MIL-STD-2105 requirements the results are considered to be of interest.

The effect of the simultaneous strike of two 0.5 inch bullets has been examined on four trials, see Table 2. These were all conducted against SSL, case bonded motors, three being filled with CDB and one with EMCDB propellant. No reaction more severe than burning was recorded on any of these trials.

Nine trials were conducted using the automatic fire of three 0.5 inch bullets, this trial being representative of the current MIL-STD-2105, BI, requirement. Information on the trials is given in Table 3. This shows that one of the SSL/EMCDBRDX motors did not react, two gave burning reactions and one resulted in deflagration. All of the steel cased motors exploded.

4 Fuel Fire Trials

Data on the results of 36 fuel fire (Fast cook-off) tests have been added to the database. The case materials used in these trials were KOA, CF, and SSL the latter with and without external insulation.

The majority of these trails were carried out in the RO RMD "mini fuel fire" hearth. The advantage of this hearth over larger hearths, such as required by MIL-STD-2105, is that less smoke is generated and it is therefore possible to observe the store during the trial. However, on occasions RO RMD has conducted trials in a large hearth and the results of these have demonstrated that comparable reaction times and responses are obtained from both large and small hearths. The data from these trials are summarised in Table 16. Details of the FCO test procedure are given in Annex C. Analysis of these data shows that in all of the 36 tests only 2 reactions more severe than burning have been recorded. One of these occurred with a case bonded CDB/SSL propellant combination, representing 7% of the 14 tests carried out, and the other was one of the two tests conducted with a carbon fibre cartridge loaded CDB/SSL combination.

No information is available in the RO RMD database on steel or aluminium cased motors. However, work reported by others suggests that reactions more severe than burning are typical of a homogenous steel case. Although the KOA results might be expected to be indicative of a homogenous Al case it should be noted that line cutting charges were used on four of these trials.

The success of the composite and SSL structures in FCO trials arises from the rapid loss in strength of the adhesive systems used in these cases at temperatures above 120°C. By the time the propellant attains its ignition temperature the case has little or no strength left and hence is unable to retain the pressure needed to support an explosion or detonation type reaction.

For air carriage applications the sensitivity of the adhesive to aeroheat induced temperature increase necessitates the use of external insulation to protect the case. Typically the equivalent of 1mm cork has been found necessary. This has led to fears that the advantage of adhesively bonded structures in FCO might be lost when the case is configured for an air carriage application. To investigate this concern RO RMD undertook a series of FCO trials on externally insulated SSL cases. The results of these trials clearly demonstrate that the effect of external insulation is to delay the time to first reaction but does not raise the level of reaction above that of burning.

5 Conclusion

5.1 0.5 inch Bullet Impact

Examination of the 165 0.5 inch bullet impact tests leads to the following conclusion for solid propellant rocket motors

i) **Temperature effects**

At temperatures below -40°C the type of case and propellant type have a second order influence on the ability of the motor to meet the IM requirements for bullet impact.

At a temperature of -50°C there is, at the 50% confidence level, a 0.91 probability of failure.

ii) **Card Gap as a predictor**

The results of trials conducted on SSL, KOA and CF cases with HTPB propellants having a card gap significantly less than 70 cards, gave marginally worse reactions than those conducted using the same cases and with EMCDB propellants having a card gap of more than 70 cards. However, only a small number of trial results are available and further work would be required to confirm this finding.

It should also be noted that the case types used in these trials were of a laminar type construction. The available data do not allow the comparison to be made for these propellants for homogenous cases, and hence the probability of an overiding case influence cannot be ruled out.

iii) **Configuration effects**

While there is an indication that case bonded motors are more likely to give reactions more severe than burning, this result may have been influenced by propellant sensitivity. More work is needed, with standardised case and propellant types to confirm this.

iv) **Case Effects**

There is strong evidence that SSL and Al cases are significantly better than homogenous steel cases. Pooling ambient trials across propellant types gives the following probabilities of failure, at the 95% confidence level, <0.11 for SSL, <0.24 for Al and <0.76 for Steel.

There is insufficient data to enable the relative performance of CF and KOA cases to be assessed.

5.2 Fuel Fire

Data from the 36 Fast cook-off trials allow the following conclusions to be made.

i) Adhesively bonded cases such as SSL and CF provide a proven means of meeting the IM requirements for FCO.

ii) To survive the aeroheat requirements of air carried missiles adhesively bonded cases need external insulation. FCO on externally insulated SSL cases have demonstrated that the time to first reaction in slightly extended but the reaction is limited to one of burning.

5.3 Mechanism of Motor Vulnerability

5.3.1 Fragment attack

When a fragment penetrates a rocket motor case it usually punches a hole at the entry point of a somewhat larger hole at the exit.

If the fragment ignites and breaks up the propellant the burning area increases and the pressure within the motor will increase rapidly. If the nozzle, fragment entry and exit areas are insufficiently large to cater for this increased pressure, high pressure failure, or even an explosion, will result.

This is the normal mechanism of fragment attack vulnerability associated with conventional steel homogenous rocket motor cases.

With a strip laminate case, the area of damage at the fragment exit point is more extensive than it would be in a conventional motor case, due to the strip delamination effect. This area appears to be proportional to the weight of the fragment. When under these conditions, the propellant ignites, gas flows out of the fragment exit hole rapidly, increases the area of delamination by a peeling back of the layers, and results in the collapse of internal pressure.

5.3.2 Fuel fire attack

When a solid propellant rocket motor is heated externally, it eventually ignites and an explosion may result due to the uncontrolled nature of the propellant self ignition. Whilst this is the mechanism of vulnerability associated with homogeneous motor cases which retain their strength well above the self ignition temperature of the propellant, this is not so with the adhesive structures. When subjected to heat, the resin used for bonding begins to break down at temperatures just above 100°C (212°F) and at 180°C (356°F) has no strength remaining. Most CDB propellants ignite at approximately 120°C (248°F) to 180°C (356°F), depending upon confinement, and clearly, from the results of the trials, when an adhesively bonded motor is subjected to a fuel fire, the resin bonding of the case breaks down faster than the propellant temperature is raised. At the instant of propellant ignition only a very low pressure is required to disrupt the motor case and thus provide a multitude of paths for gas and to exhaust and thereby prevent an explosive pressure build-up.

5.3.3 Design Criteria for I.M.

RO RMD has been able, through the extensive range of trials and subsequent analysis, to define design criteria for I.M. which are currently being used with solid propellant rocket motor designs.

Annex A

Strip Laminate Rocket Motor Cases

1.0 What is Steel Strip Laminate?

Strip Laminate rocket motor cases are made by helically winding a number of layers of metal strip coated with a suitable adhesive onto a mandrel of diameter equal to the desired bore of the finished tube.

When subjected to mechanical loads bodies made by the SSL process behave in the same manner as homogeneous bodies of the same material strength.

Details of the history behind this process and a description of the manufacturing technique are given in the following sections:-

1.1 History

The Steel Strip Laminate (SSL) technique of rocket motor case manufacture was perfected at Royal Ordnance RMD in the early 1950's. The simplicity, flexibility and short lead time of the manufacturing process were the key motivating factors driving development, but the ability to utilise ultra high strength steels was an added attraction of this unique method of case construction.

Only later did the Insensitive Munitions (IM) properties of SSL become apparent. When SSL rocket motors were subjected to bullet impact and fuel fire trials benign reactions, now known to be typical of these motors, were achieved. During the period 1972 to 1990 in excess of 200 SSL motors were subjected to a range of IM tests of which around 40 were fuel fire trials with the majority of the remainder being projectile impact tests.

Since its development SSL cases with diameters in the range of 60mm to 600mm and lengths of up to 3000mm have been produced. Bodies have been subjected to pressures of up to 600 bar, operational temperatures as low as -54°C and as high as 71°C, tropical storage, severe flight loading in missile structures and rough handling trials.

SSL cases have been in volume production since the late 1950's for a number of missile systems, notably Rapier and more recently the vertical launch Seawolf. To date around 40 000 production motors and numerous development motors have been produced with SSL cases.

1.2 Manufacturing Process

Currently two specifications of steel strip, a 0.7%C/2.0%Ni steel and a 7%NI/17%Cr stainless steel, ae used in SSL tube production. Both of these materials have an ultimate strength in the region of $2GN/m^2$. However, the strip laminate technique has also been successfully applied with aluminium alloy, titanium alloy and maraging steel.

Strip is received from the supplier in 300m (1000ft) lengths in coil form, typical dimensions of the strip, suitable for diameters greater than 100mm (4 inch), are 100mm (4 inch) wide by 0.25mm (0.01 inch) thick.

Prior to winding the strip is prepared by passing it through a degreasing solution to remove oil, shot blasting both sides to remove oxides and texture the surface and then passing it for a second time through a degreasing solution. A thin layer of an epoxide adhesive is applied to the strip and dried in a heated tower. The coated strip is then recoiled and may be stored for up to six months without deterioration of the adhesive or metal strip.

The metal strip is helically wound onto a heated mandrel so that there is a small gap between successive turns of the helix. Additional layers of strip are added until the desired thickness is obtained, each layer is wound in the same direction but the helices are staggered.

When winding is complete the mandrel temperature is increased to partially cure the adhesive. After an appropriate time the mandrel is cooled and the tube is removed and cut to length.

End fittings and any other attachments, such as launch feet, are then bonded onto the tube. The surfaces to be bonded are prepared by shot blasting, degreasing and priming. The tube and components are assembled into a jig, to ensure accuracy of alignment, adhesive is pumped in to the bonding cavities and the whole assembly transferred to an oven for final cure.

The finished motor body may be lined, painted and filled in exactly the same way as a body made by an other process.

Annex B

Bullet Impact Test Procedure

The general arrangement of the test set up is shown in Figure B1.

The motor mounting rig is rigidly located such that its longitudinal axis is at 90° to the line of fire of a 0.5" Browning machine gun, positioned at a distance of 30m ± 0.5m. The gun barrel is at the same height as that of the centre point of the target. Blast overpressure gauges, Piezo Electric Type 'B', are positioned either side of the mounting rig at 45° right and 135° left to the line of gun fire and at distances of 1m, 2m and 5m from the point of impact and exit on the motor.

Bullet velocity measuring equipment, cine cameras and a colour VCR are located as shown in Figure B1.

The gun is prepared by firing 'warmers' and zeroing rounds.

When all items are sited and their operation has been satisfactorily confirmed the motor is taken from the conditioning chamber and positioned into the test rig. The gun is zeroed on to the aiming point of the motor and an instant of strike foil switch is attached to the motor over the aiming point. The gun is loaded and all instrumentation is started. When recording equipment is at operating speed the gun is fired.

After firing, still photographs of the rocket motor debris are taken before any hosing down or manual disturbance. A record is also made of the type of damage to the motor and rig, distance, direction, dimensions and weight of any debris.

A tabulation of peak overpressure, shock arrival time and duration of pulse is obtained for each overpressure gauge and a time trace of pressure is also produced.

Annex C

Fast Cook Off Test Procedure

RO (RMD) Mini Fuel Fire

The motor mounting rig also contains its own fuel hearth and is constructed from 3 x 62" lengths of 15" x 4" RSC, welded together to form a tray 62" x 45" x 4" into which the motor support cradle is fitted such that the bottom of the store is not less than 0.2m above the fuel surface.

This rig is placed in the centre of the fuel fire arena. Piezo Electric blast gauges Type 'A' (2 off) are positioned 3m from the store (either side).

The rocket motor is secured into the rig. Two flame temperature thermocouples are situated 10mm below the centre of the motor, off set 40-60mm either side and connected to a recorder. See Figure C1.

Sufficient fuel (AVCAT) or commercial Kerosene Grade 'B' (DEF 2403) to sustain a 10 minutes fire is poured into the hearth. Water from a low pressure supply is then added until the level of the fuel is 0.2m below the bottom of the store. To aid ignition, petrol is floated on top of the fuel. The petrol is ignited by means of an electrically initiated puffer inserted into an opened Mortar Augmenting charge, surrounded in petrol soaked cotton waste.

A colour cine, framing at 100pps, running for 2.5 minutes and colour video camera with VCR, sound and CCTV are employed to record the trial events.

The temperature from the thermocouples, the time from ignition to the attainment of a flame temperature of 550°C and the time from 550°C to motor failure is recorded. A graph of flame temperature versus time from fuel ignition to motor failure is produced. Data from blast overpressure gauges are also tabulated and plotted.

Acknowledgment

This work has been carried out with the support of Procurement Executive Ministry of Defence.

		HTPB				EMCDB			EMCDB RDX		CDB								CDB RDX			Cordite	CMCDB	
											CI			CB					CI		CB	CI	CI	CB
		50	30	20	+60	50	30	+60	40	AMB	30	AMB	+60	50	40	30	AMB	+60	30	+60	30	AMB	AMB	AMB
SSL	NR								1	2					2									
	B		1		1		1	1		5			1				16	1		1				
	D																							
	E	1				1					1								1					
	Det																							
Steel	NR											1												
	B											17					3					5	1	
	D																					1	2	
	E											25					11					16	1	2
	Det																							
KOA	NR																							
	B						1	1										2						
	D				1																			
	E	1		1		1										1					1			
	Det																							
CF	NR							1																
	B		1				1						1							1				
	D				1																			
	E	1				1					1										1			
	Det													1										
Al	NR											7												
	B											4												
	D																							
	E																							
	Det																							

NR No Reaction
B Burning Reaction
D Deflagration
E Explosion
Det Detonation

TABLE 1 0.5 INCH SINGLE BULLET IMPACT

CLASS 1.1 PROPELLANT *

		EMCDB			EMCDB RDX		CDB						CDB RDX			CMCDB	
							CI		CB				CI		CB	CI	CB
		-50	30	+60	40	AMB	30	+60	-50	30	AMB	+60	30	+60	30	AMB	AMB
SSL	NR				1	2											
	B		1	1		5		1			2			1			
	D																
	E	1					1						1				
	Det																
Steel	NR																
	B										2					1	
	D															2	
	E										10					1	2
	Det																
KOA	NR																
	B		1	1								2					
	D																
	E	1								1					1		
	Det																
CF	NR			1													
	B		1					1						1			
	D																
	E	1					1								1		
	Det								1								

* BASED ON US CARD GAP DEFINTION

TABLE 1a 0.5 INCH SINGLE BULLET TRIALS/CLASS 1.1 PROPELLANT

CLASS 1 3 PROPELLANT *

		HTPB				CDB					Cordite
						CL		CB			
		50	30	20	+60	AMB	+60	40	AMB	+60	AMB
SSL	NR							2			
	B		1		1				14	1	
	D										
	E	1									
	Det										
Steel	NR					1					
	B					17			1		5
	D										1
	E					25			1		16
	Det										
KOA	NR										
	B										
	D				1						
	E	1		1							
	Det										
CF	NR										
	B		1								
	D				1						
	E	1									
	Det										
Al	NR					7					
	B					4					
	D										
	E										
	Det										

* BASED ON US CARD GAP DEFINTION

TABLE 1b 0.5 INCH SINGLE BULLET IMPACT TRIALS/CLASS 1.3 PROPELLANT

IM Database

CASE MATERIAL \ PROPELLANT		CDB		EMCDB/RDX	
		CB AMB	CL	CB AMB	CL
SSL	NR				
	B	3		1	
	D				
	E				
	Det				

TABLE 2

SIMULTANEOUS STRIKE OF TWO 0.5 INCH BULLETS

CASE MATERIAL \ PROPELLANT		CDB		EMCDB/RDX				Cordite	
		CB	CL	CB			CL	CB	CL
		AMB	AMB	-40	AMB	+60			
SSL	NR				1				
	B			1		1			
	D				1				
	E								
	Det								
Steel	NR								
	B								
	D								
	E	1	1						3
	Det								

TABLE 3

THREE ROUNDS AUTOMATIC FIRE OF 0.5 INCH BULLETS

KEY:

NR	No Reaction	E	Explosion
B	Burning Reaction	Det	Detonation
D	Deflagration		

IM Database

PROPELLANT / CASE MATERIAL	CDB		EMCDB		HTPB		Cordite		CMCDB	
	CB	CL	CB	CL	CB	CL	CB	CL	CB	CL
SSL			11							
Steel		13						2		

TABLE 4 7.62 mm BULLET IMPACT TRIALS

PROPELLANT / CASE MATERIAL	CDB		EMCDB		HTPB		Cordite		CMCDB	
	CB	CL	CB	CL	CB	CL	CB	CL	CB	CL
SSL	9		5							
Steel	4	15						4	1	

TABLE 5 20 mm BULLET IMPACT TRIALS

PROPELLANT / CASE MATERIAL	CDB		EMCDB		HTPB		Cordite		CMCDB	
	CB	CL	CB	CL	CB	CL	CB	CL	CB	CL
SSL										
Steel		12								

TABLE 6 3.5g FRAGMENT PROJECTILE IMPACT TRIALS

PROPELLANT / CASE MATERIAL	CDB		EMCDB		HTPB		Cordite		CMCDB	
	CB	CL	CB	CL	CB	CL	CB	CL	CB	CL
SSL										
Steel		5								

TABLE 7 17g FRAGMENT PROJECTILE IMPACT TRIALS

IM Database

CASE MATERIAL \ PROPELLANT	CDB		EMCDB		HTPB		Cordite		CMCDB	
	CB	CL	CB	CL	CB	CL	CB	CL	CB	CL
SSL	9									
Steel										

TABLE 8 0.3 mm BALL AMMUNITION IMPACT TRIALS

CASE MATERIAL \ PROPELLANT	CDB		EMCDB		HTPB		Cordite		CMCDB	
	CB	CL	CB	CL	CB	CL	CB	CL	CB	CL
SSL										
Steel		5								

TABLE 9 20 mm BALL IMPACT TRIALS

CASE MATERIAL \ PROPELLANT	CDB		EMCDB		HTPB		Cordite		CMCDB	
	CB	CL	CB	CL	CB	CL	CB	CL	CB	CL
SSL	72		12							
Steel									2	

TABLE 10 105 mm SHELL TRIALS

CASE MATERIAL \ PROPELLANT	CDB		EMCDB		HTPB		Cordite		CMCDB	
	CB	CL	CB	CL	CB	CL	CB	CL	CB	CL
SSL										
Steel	2									

TABLE 11 84 mm SHELL TRIALS

IM Database

PROPELLANT / CASE MATERIAL	CDB		EMCDB		HTPB		Cordite		CMCDB	
	CB	CL	CB	CL	CB	CL	CB	CL	CB	CL
SSL	6									
Steel										

TABLE 12 DETONATION 109 TRIALS

PROPELLANT / CASE MATERIAL	CDB		EMCDB		HTPB		Cordite		CMCDB	
	CB	CL	CB	CL	CB	CL	CB	CL	CB	CL
SSL	17									
Steel										

TABLE 13 DETONATION TRIALS

PROPELLANT / CASE MATERIAL	CDB		EMCDB		HTPB		Cordite		CMCDB	
	CB	CL	CB	CL	CB	CL	CB	CL	CB	CL
SSL	22		2							
Steel								2		

TABLE 14 SYMPATHETIC DETONATION TRIALS

IM Database

CASE MATERIAL \ PROPELLANT	CDB		EMCDB		HTPB		Cordite		CMCDB	
	CB	CL	CB	CL	CB	CL	CB	CL	CB	CL
SSL	4									

TABLE 15 SHAPED CHARGE TRIALS

CASE MATERIAL	\ PROPELLANT	CDB		EMCDB		HTPB		Cordite		CMCDB	
		CB	CL	CB	CL	CB	CL	CB	CL	CB	CL
SSL	NR										
	B	13	1	5+4AH		1					
	D										
	E	1									
	Det										
KOA	NR										
	B	1+2LC		1+1LC		1+1LC					
	D										
	E										
	Det										
CF	NR										
	B		1	1		1					
	D										
	E		1								
	Det										

TABLE 16 FAST COOK-OFF TRIALS

KEY:
- NR No Reaction
- B Burning Reaction
- D Deflagration
- E Explosion
- Det Detonation
- LC Line Cutting Charge
- AH Aeroheat Protected

CASE MATERIAL \ PROPELLANT	CDB		EMCDB		HTPB		Cordite		CMCDB	
	CB	CL	CB	CL	CB	CL	CB	CL	CB	CL
SSL	4									

TABLE 17 FLAME IMPINGEMENT TRIALS

	HTPB		EMCDB		EMCDB/RDX		CDB		CDB/RDX		CMCDB	
	P	F	P	F	P	F	P	F	P	F	P	F
SSL	2		2		7		2					
Steel							2	10				2
KOA		2	2				2	1		1		
CF	1	1	2							1		

TABLE 18

RESULTS OF 0.5 INCH SINGLE BULLET IMPACT TEST AGAINST CASE BONDED, HTPB AND CLASS 1.1* DOUBLE BASED PROPELLANTS AT $\geqslant -30^{0}$C

* US DEFINITION BASED ON CARD GAP

Figure No B1 - Plan of Trials Arena

Gauge No	Distance (m)	Gauge No	Distance (m)
1	1	4	1
2	2	5	2
3	5	6	5

Legend

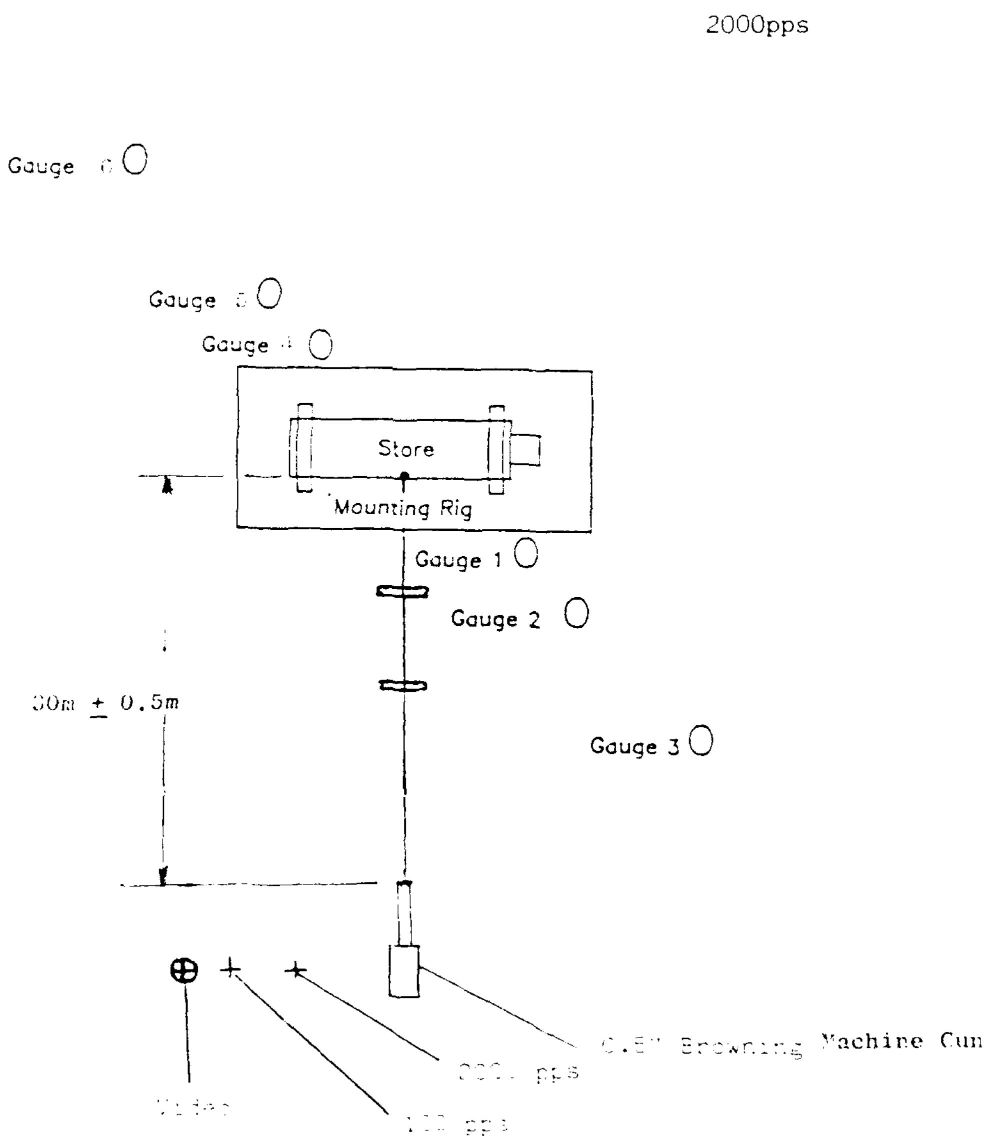
PPS Pictures per second

Blast Overpressure Gauges

Cine Cameras

Video Camera

Velocity Cells



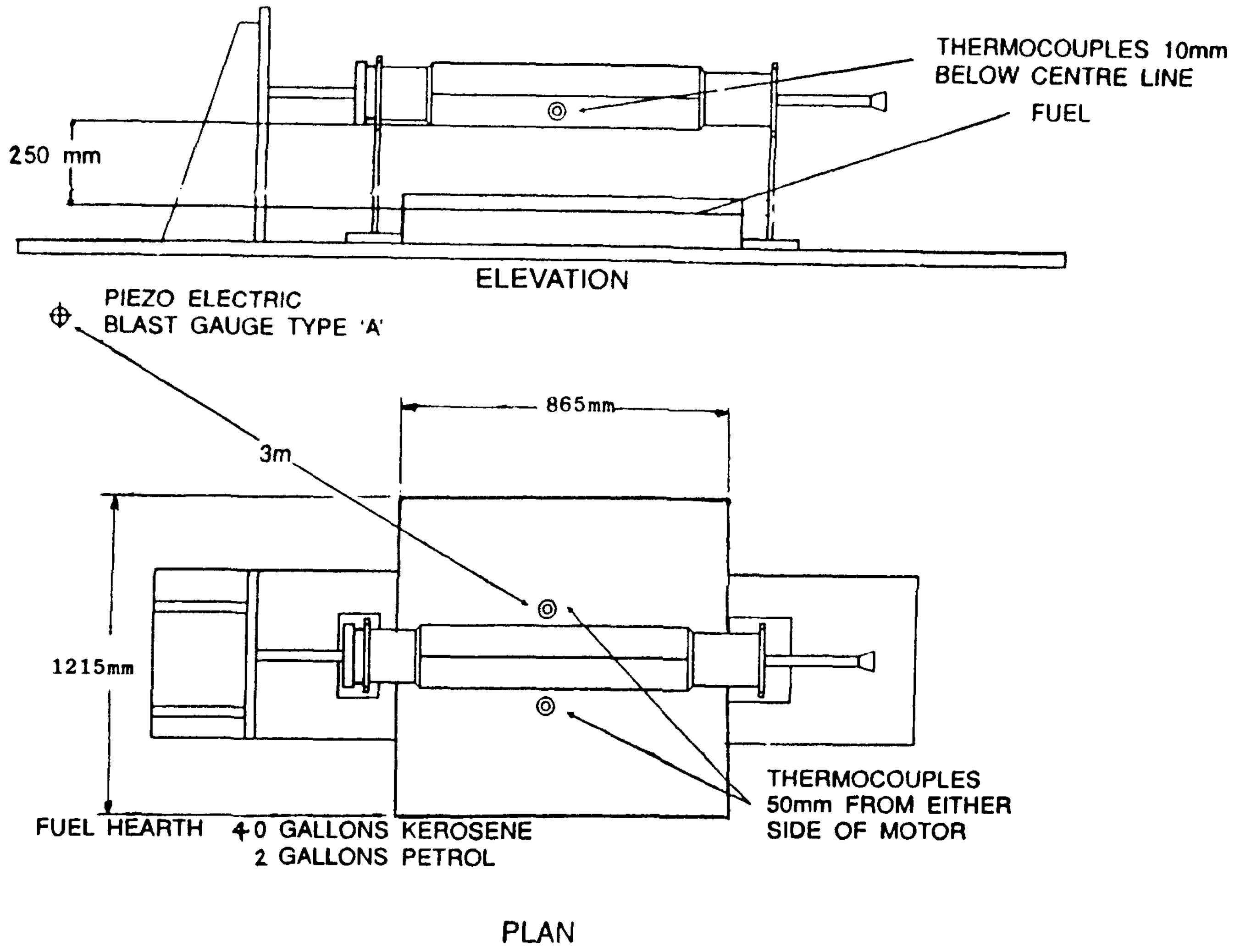


Figure No C1 - Mini Fuel Fire Arrangements

Discussion

QUESTION BY ZELLER, FRANCE: Can you give some information, even only qualitative, on sympathetic detonation test results?

ANSWER: The sympathetic detonation trials conducted by RO RMD differ significantly from those prescribed in the MIL-STD and STANAG documents. In the RO RMD test the donor motor is prepared packing the conduit with explosive and electrically initiating. The receptor motor is placed in close proximity, in some cases touching, to the donor motor. A total of 13 trials of this type have been carried out, all gave violent reactions, i.e. 6 detonations and 7 explosive events.

QUESTION BY VICTOR, US: In the chart that showed fast cook-off results the time delay for CDB propellants was longer than for both EMCDB and HTPB propellants. I wondered if the CDB results were due to the type or amount of insulation used in the KOA or CF cases.

ANSWER: The results presented for the times to first reaction did not discriminate between cartridge loaded and case bonded charges. The data has been re-examined to present the results of these different loading arrangements separately, see figures in the paper. The figures heading each column indicate the number of trials conducted for each case/propellant combination. While presenting the data in this way removes the anomaly identified in the question in relation to CDB propellants it does not validate the conclusion drawn from this work. That is that the reaction times for all three case bonded propellants tested in SSL cases are similar and that the reaction time for EMCDB propellant appears to be independent of the case construction tested. The insulation standard was similar for all case/propellant combinations and therefore the longer time to first reaction of the KOA/HTPB motor would appear to be related to the difference in case construction.

HAZARDS REDUCTION FOR TACTICAL MISSILES

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1.0 SUMMARY

Substantial progress has been made over the past four years in characterizing and understanding the response of energetic materials and rocket motors to the energetic stimuli specified in MIL-STD-2105A. Approaches to reducing the sensitivity based upon that work are reviewed. Minimum smoke propellants with an improved performance-shock sensitivity balance have been formulated. Partial or complete replacement of the nitramine with phase stabilized ammonium nitrate reduced the shock sensitivity significantly at a performance loss of 4-10%. A number of routes to more extinguishable composite propellants, both reduced smoke and high performance types, are discussed. Replacement of the polybutadiene with alternative polymeric backbones has yielded more extinguishable compositions. The use of metal perchlorates in place of the ammonium perchlorate greatly increases thermal stability. In the area of inert components, alternatives to monolithic metal cases, such as composites cases, substantially improve the response to fast cook-off and, for minimum smoke propellants to bullet impact.

2.0 LIST OF SYMBOLS

IM	Insensitive Munitions
AP	Ammonium perchlorate
Al	Aluminum
EPDM	Ethylene propylene dimer
BI	Bullet Impact
FCO	Fast cook-off
SCO	Slow cook-off
SD	Sympathetic detonation
SCJ	Shaped charge jet
HTPB	Hydroxyterminated polybutadiene
C_d	Critical diameter-smallest diameter at which a detonation propagates
RDX	1,3,5-trinitrazacyclohexane
HMX	1,3,5,7-tetranitrazacyclooctane
PSAN	Phase stabilized ammonium nitrate
Hex	Heat of explosion (cal/g)
XLDB	Crosslinked double base propellant
CDB	Cast double base
PMCDB	Polymer modified cast double base
KP	Potassium perchlorate
Vb	Velocity at burnout
DOD	Department of Defense

3.0 INTRODUCTION

During the 1980's the Department of Defense initiated the Insensitive Munitions program, a comprehensive effort to reduce the sensitivity of their munition systems. The goal of this program is to develop munitions fulfilling their performance and operational requirements while minimizing the violence of reaction and subsequent damage when subjected to unplanned stimuli [Ref 1,2]. Over the preceding 25 years, a series of incidents involving carrier fires, storage depots and rail/highway transportation accidents demonstrated the need for Insensitive Munitions.

MIL-STD-2105A, in which the Insensitive Munitions requirements are defined, was issued in 1991 by the U.S. Navy [Ref 3]. The standard, which is summarized in Table 1, defines test conditions and criteria necessary to determine the munition response to the principal threats. The standard also requires the weapons system program managers to assess the threat to the weapon system and prepare a test plan for approval by the Service's Explosive Safety Review Board. The review board has the authority to invoke or waive the criteria set forth in MIL-STD-2105A. Meeting the IM standard is not a matter of satisfying a single requirement rather seven separate criteria must be met.

Designing missiles to meet the IM criteria is complex because, in general, the nature of the response to each of the energetic stimuli depends on different characteristics of the missile or motor. For instance the response of a typical rocket motor to shaped charge jet is largely controlled by the shock sensitivity of the propellant while the response to fast cook-off (FCO) and slow cook-off (SCO) is dependent mainly on venting the case

to relieve the pressure. Table 2 shows the principal factors controlling the response of rocket motors to the energetic stimuli addressed in MIL-STD-2105A. Similar relationships would be applicable to warheads, although the relative importance would change because of the heavier walls and necessary detonability of the explosive load. A system approach is required to meet the IM goals since different features/characteristics of the motor are involved in meeting the criteria.

TABLE 1
IM CRITERIA ESTABLISHED IN MIL-STD-2105A

TEST	CONDITION	CRITERIA
Sympathetic Detonation	Detonate one of two units in shipping/storage configuration	No detonation of acceptor
Fast Cook-Off	Jet Fuel Fire 1600°F	Burning
Bullet Impact	Three .50 cal at 2,800 ft/sec	Burning
Fragment Impact	Two 1/2" Fragments at 8,300 ft/sec	Burning
Slow Cook-Off	6°F/Hr	Burning
Shaped Charge Jet	81mm shape charge or M42/M46	No detonation
Spall	81mm shape charge through armor plate	No sustained burning

TABLE 2
FACTORS DETERMINING ROCKET MOTOR
RESPONSE TO ENERGETIC STIMULI

THREAT	CRITICAL RESPONSE FACTORS
Propagation of Detonation to adjacent Units	1. Propellant Shock Sensitivity 2. Case - Fragmentation 3. Shipping Container - Attenuation
Fire	1. Case Venting - Temperature 2. Propellant
Bullets	1. Propellant - Extinguishability, Toughness 2. Case Configuration
High Velocity Fragments	1. Propellant - Shock Sensitivity, Toughness 2. Shipping Container - Attenuation
Slow Heating	1. Case Venting - Temperature/Pressure 2. Propellant Stability, Decomposition
Shaped Charge	1. Propellant Shock Sensitivity
Spall	1. Propellant Stability, Extinguishability 2. Case

As indicated in Figure 1, this approach entails a coordinated program involving the development of less sensitive propellants, explosives and ignition devices as well as venting devices and case materials that mitigate the response to energetic stimuli. In addition, techniques to predict the response of missiles based on material properties and configurations are needed because the test series required by MIL-STD-2105A is very expensive. In general, a minimum of 20 missiles are required to conduct the specified tests. Hence, the combined cost of the test and missiles precludes the full scale evaluation of a large number of options.

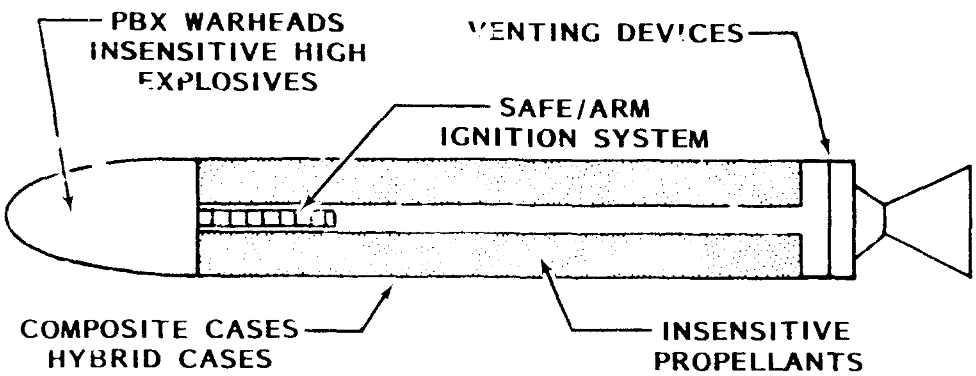
Significant progress has been made since the mid-eighties in DOD and industry laboratories, as well as in NATO countries, in characterizing and understanding the response of energetic materials, rocket motors, and warheads to the stimuli specified in 2105A. As a result of this work, a number of promising approaches to meeting the IM criteria have been identified [Ref 4]. Government and industry have committed substantial funds to pursue this research and initiate the development programs necessary to incorporate IM technology into deployed missile systems [Ref. 5-12]. While a comprehensive program which includes all aspects of developing missiles is needed to meet the IM criteria, this paper focuses primarily on the rocket motor.

The propellant is of paramount concern with all of the IM criteria. Current rocket propellants can be divided into two broad families (Table 3) in terms of their behavior with the IM stimuli. The principal problem with minimum smoke propellants, which are based on nitrate ester and nitramine, is shock sensitivity. Conversely, reduced smoke propellants, which are based on ammonium perchlorate (AP) and an elastomeric

TABLE 3
RESPONSE TO INITIATION STIMULI VARIES WITH PROPELLANT TYPES

			HIGH ENERGY PROPELLANTS	
INGREDIENTS	MINIMUM SMOKE %	REDUCED SMOKE %	AL/XLDB %	AL/AP/HTP %
Nitrate Ester	20 - 30	--	15 - 20	--
Nitramine	50 - 65	--	30 - 40	--
Polymer	5 - 10	--	5 - 10	--
Modifiers	2 - 5	2 - 5	2 - 5	2 - 5
AP	--	85 - 91	5 - 10	70 - 80
HTPB	--	7 - 12	--	7 - 12
Al	--	--	10 - 20	10 - 20
PARAMETERS				
Isp* (sec)	248	248	272	268
Card Gap	>100	0	>100	0
Critical Diameter	<20mm	>1m	<20mm	>1m
Cook-Off (Vented)	Burning	Burning-Explosive	Burning	Burning/Explosive

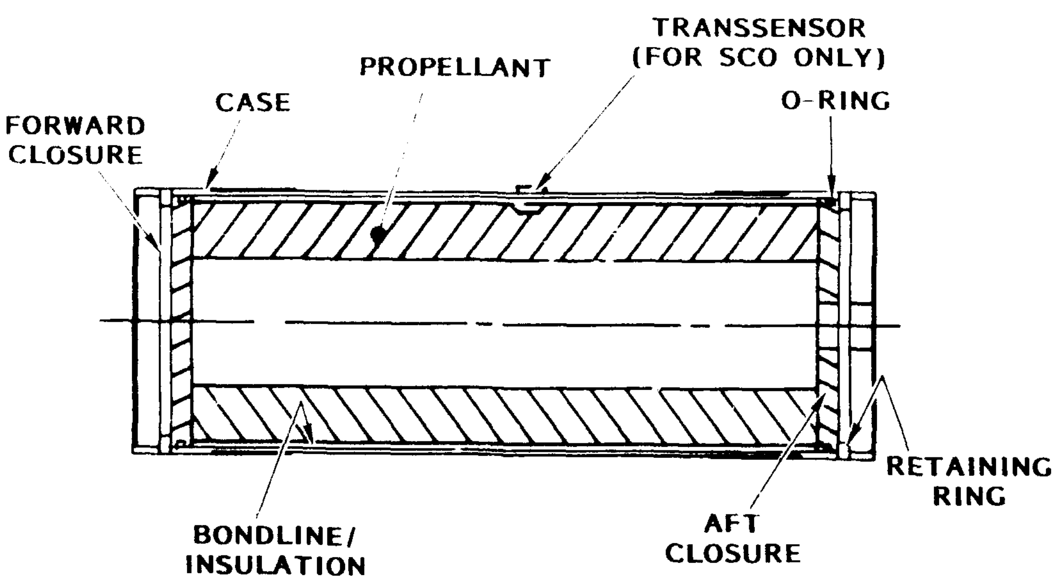
FIGURE 1
A SYSTEM ORIENTED PROGRAM IS REQUIRED TO MEET IM CRITERIA



SUPPORTING SYSTEM STUDY AREAS

- MUNITIONS STORAGE & TRANSPORTATION
- HAZARDS ASSESSMENT/ANALYSIS
- COMPUTER MODELING

FIGURE 2
IM GENERIC TEST MOTOR



polymer (usually urethane cured polybutadiene) are relatively insensitive to shock but burn vigorously at low pressure and are difficult to extinguish. Composite propellants also tend to react very violently in the slow cook-off test, even with minimal confinement. Table 3 shows that the addition of aluminum (Al) gives higher energy propellants which largely retain the sensitivity characteristics of the base compositions. In this paper progress in developing both insensitive minimum smoke and composite propellants is discussed.

4.0 RESULTS AND DISCUSSION

4.1 PROPELLANT-CASE INTERACTION

To increase understanding of the factors that control the response to energetic stimuli and to provide guidance in designing less sensitive rocket motors we conducted a series of IM tests on generic motors in which the material of case construction and the propellant were systematically varied as shown in Table 4. Both class 1.1 minimum smoke propellants and class 1.3 composite propellants were compared in monolithic steel and aluminum, graphite composite, and steel strip laminate cases. The composition and characteristics of the propellants are given in Table 3. In addition to these propellants a class 1.3 minimum smoke formulation was tested, primarily in graphite composite cases. As Table 4 shows the first series of tests involved only bullet impact, fast and slow cook-off.

TABLE 4
MOTOR RESPONSE WAS DETERMINED AS FUNCTION OF PROPELLANT/ CASE MATERIAL COMBINATION

CASE MATERIAL	PROPELLANT	
	MIN SMOKE	REDUCED SMOKE
Graphite Composite	B, S, F	B, S, F
Strip Laminate (Steel)	B, S, F	B, S, F
Al	B, S, F	B, S, F
Steel	B, S, F	B, S, F

B = Bullet Impact, S = Slow Cook-Off,
F = Fast Cook-Off

A schematic of the five-inch diameter generic motor is shown in Figure 2. Most of the tests were conducted with a one-inch web at which the generic motor holds approximately 4.5 kg of propellant. Currently work is being carried out with a two-inch web (6 kg of propellant). The properties of the various case materials in this configuration are summarized in Table 5. The failure pressure varies from 3500 to 5600 psi (25 to 39 Mpa). The insulation is EPDM with a thickness of 0.76 mm. One closure has a 22 mm diameter port to simulate a nozzle throat.

The generic motor tests were carried out at the Hercules IM test facility located at Allegany Ballistics Laboratory, Rocket Center, WV. Larger scales tests are conducted at the Bacchus works, Magna, UT. The tests were instrumented with video camera and airblast gauges. Thermocouples were included in the motors for the cook-off tests and gauges to measure gas pressure in the propellant grain were incorporated for some of the slow cook-off tests. High speed (10,000 frames/s) photographic coverage was used for the bullet impact, sympathetic detonation, and shape charge jet tests. Steel witness plates were used in the sympathetic detonation and shaped charge jet tests. Fast cook-off and slow cook-off were done in accordance with MIL-STD-2105A. A schematic of the experimental arrangement for slow cook-off is shown in Figure 3. A single .50 caliber round was used for BI, in contrast to the 3-round burst within 50ms specified in the standard. This was deemed adequate for the purpose of the current study which was to establish design guidelines rather than qualification of a weapon system.

The bullet impact test results for Class 1.1 minimum smoke and reduced smoke propellants are summarized in Table 6. The case material had a very strong effect on the response of Class 1.1 minimum smoke propellants to bullet impact. With the steel case the reaction was a deflagration or explosion while with the composite case no reaction (light or smoke) was observed. With the strip laminate case the propellant extinguished immediately after impact with negligible consumption of propellant. A mild burn was observed with the Al case. Photographs of the motors after the test are shown in Figure 4. Clearly all of the reactions were mild except for the steel case which was thrown about eighty feet. These results are consistent with those reported by Thorn [Ref 13] who conducted multiple tests with various size bullets- composite cases gave no reaction or burns while Al cases gave mostly burns. However, a small but significant fraction of the bullet impact tests with Al cases resulted in explosion or detonation.

With the reduced smoke composite propellant, case material had less effect on the response to BI than it did with the Class 1.1 minimum smoke propellant.

FIGURE 3
THE SLOW COOK-OFF TEST ARRANGEMENT

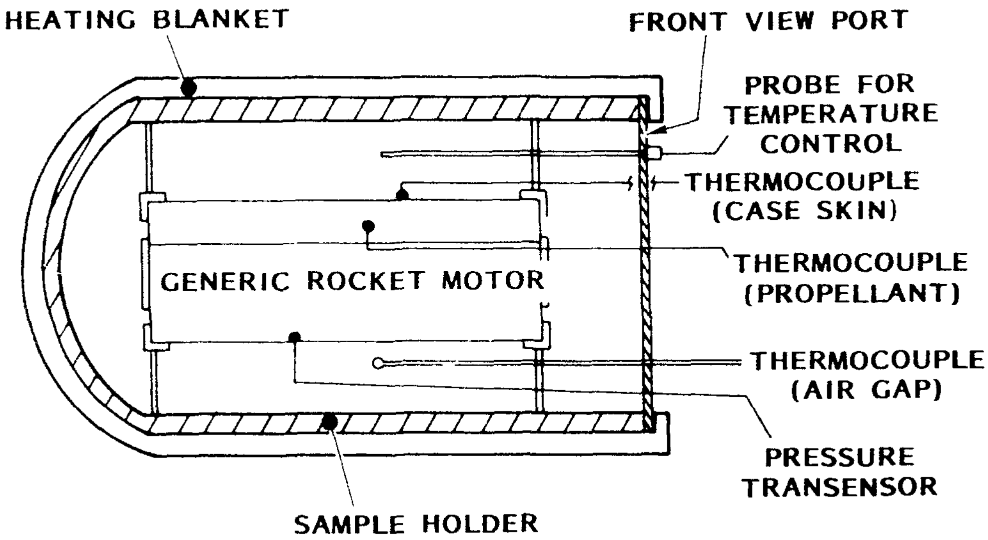
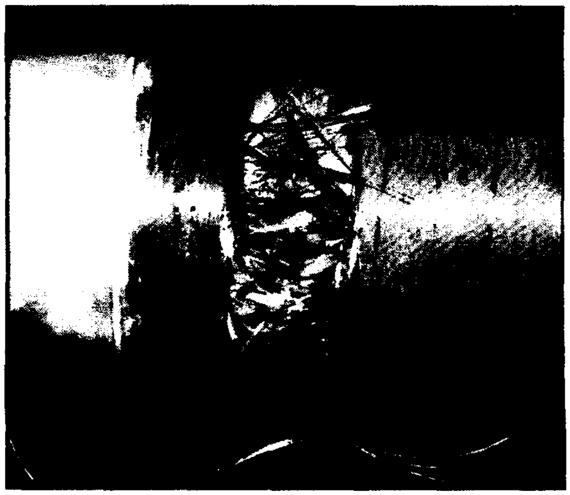


TABLE 5
GENERIC CASES REPRESENT A VARIETY OF
MATERIALS AND CONSTRUCTION TECHNIQUES

TYPE	FAILURE PRESSURE (MPa)	THICKNESS (MM)	END RING (RESIN)	CASE RESIN	
				EPOXY AMINE	SOFTENING TEMPERATURE (°C)
Composite	39	1.8	EA934	55A	127
Strip Laminate	35	1.2	9414	9379	178
Aluminum	25	3.5	N/A	N/A	N/A
Steel	30	3.5	N/A	N/A	N/A

NOTE: Insulator - 0.76mm thick EPDM for all cases.

CLASS 1.1 MINIMUM SMOKE PROPELLANT BI TESTS

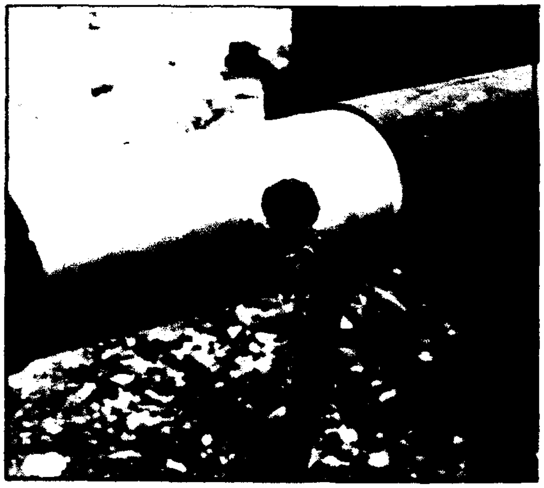


GRAPHITE COMPOSITE CASE

NO REACTION TO BI

STRIP LAMINATE CASE

BURNING, FOLLOWED BY PROPELLANT EXTINGUISHMENT



ALUMINUM CASE

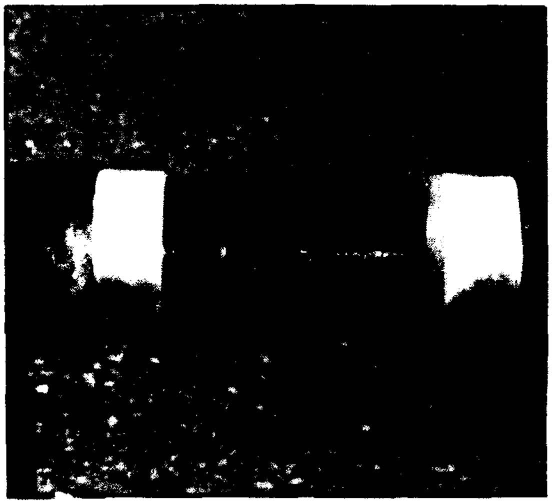
PROPELLANT BURNED

STEEL CASE

PROPELLANT DEFLAGRATION

FIGURE 4
GRAPHITE COMPOSITE CASE GAVE MILDEST RESPONSE IN BULLET IMPACT TESTS WITH CLASS 1.1 MINIMUM SMOKE PROPELLANT

CLASS 1.3 REDUCED SMOKE PROPELLANT BI TESTS



GRAPHITE COMPOSITE CASE

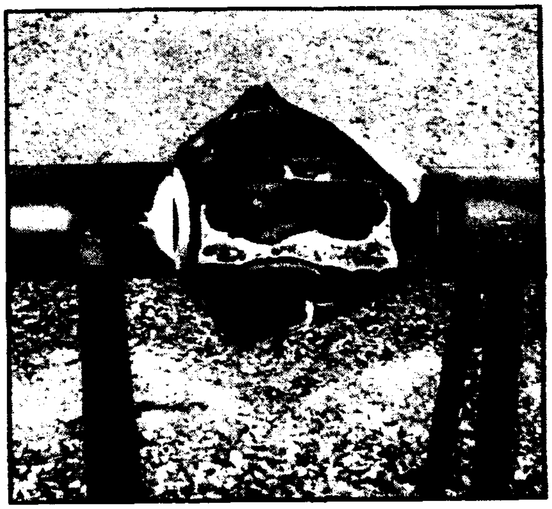
PROPELLANT BURNED

STRIP LAMINATE CASE

PROPELLANT BURNED

ALUMINUM CASE

PROPELLANT BURNED,
CASE SPLIT



STEEL CASE

PROPELLANT BURNED,
CASE SPLIT

FIGURE 5
BULLET IMPACT TESTS OF CLASS 1.3 REDUCED SMOKE PROPELLANTS
RESULTED IN BURNING IN ALL THE GENERIC TEST MOTORS

TABLE 6
BULLET IMPACT TESTS ON GENERIC MOTORS

CASE MATERIAL	CLASS 1.1 MIN SMOKE	REDUCED SMOKE
Composite	No Reaction	Burn
Strip Laminate	Extinguished	Burn
Aluminum	Burn	Burn (Case Split)
Steel	Deflagration	Burn (Case Split)

TABLE 7
SUMMARY OF FAST COOK-OFF TESTS
WITH GENERIC MOTORS

SMOKE CASE MATERIAL	CLASS 1.1 MINIMUM SMOKE PROPELLANT	REDUCED SMOKE PROPELLANT
Graphite	Burned	Burned
Strip Laminate	Burned	Burned
Aluminum	Burned	Burned
Steel	Ejected Closure	Propulsive Burning

As Table 6 shows a burning response was observed for all four case materials, with the composite and strip laminate giving a milder burn than the monolithic metal cases. A very energetic response was observed with the monolithic steel and Al cases as the photographs in Figure 5 indicate. Hence it may be anticipated that with larger motors a deflagration or explosion could result. This was in fact observed in NWC tests with Shrike motors using steel cases. (Ref. 14).

Both the minimum smoke propellant and the composite propellant motors passed the FCO test with graphite composite, strip laminate, and Aluminum cases (Table 7). With all three materials the case thermally degraded before propellant ignition, thereby providing adequate venting. The steel case failed with both propellant types, by ejecting the closure with the minimum smoke propellant and by a propulsive burn with the composite propellant. These tests show that construction of the case to provide adequate venting will allow the FCO criteria to be met. Clearly, the thickness and location of the insulation will be critical when Al is used as the case material.

The minimum smoke propellant passed the SCO test in the composite case with a mild reaction after ejection of the end ring (Table 8). The ignition temperature for the minimum smoke propellant was ~130°C as shown in Figure 6. The end ring was bonded with an adhesive that should shear or fail adhesively at that temperature. The internal gas pressure in the propellant increased by only 10 psi (69kPa) prior to ignition.
The pressure was measured by a transensor mounted on the case wall. With Al or steel cases the ignition temperature was the same, as expected, however, the response upon ignition was an explosion or detonation since there was no venting mechanism except for the throat opening.

The composite propellant motors failed the SCO test with all four case materials. The reaction in each instance was an explosion which fragmented not only

FIGURE 6
DIFFERENT PROPELLANT TYPES GAVE WIDELY VARYING RESPONSES IN SLOW COOK-OFF TEST

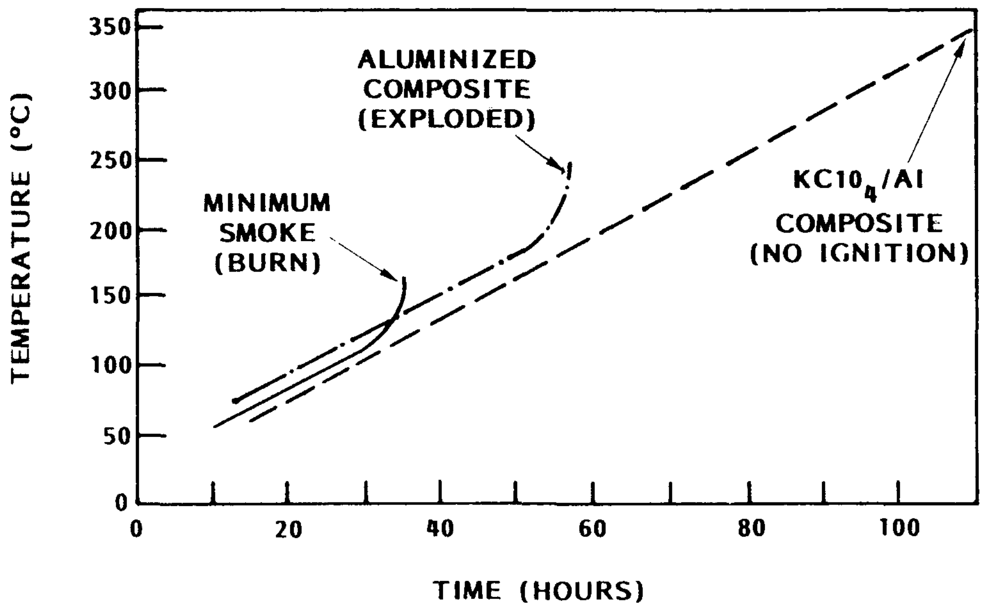


FIGURE 7
EFFECT OF HMX CONTENT ON THE SDT SENSITIVITY OF MINIMUM SMOKE PROPELLANTS

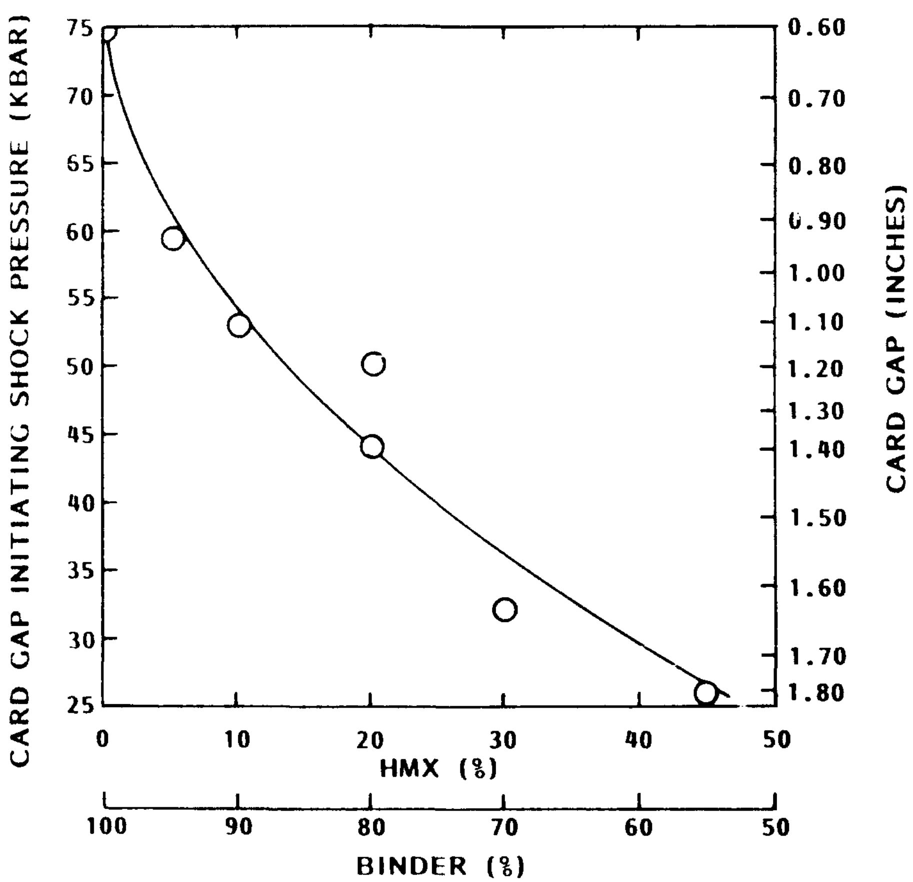


TABLE 8
SLOW COOK-OFF TESTS WITH GENERIC MOTORS

CASE MATERIAL	CLASS 1.1 MINIMUM SMOKE PROPELLANT	REDUCED SMOKE PROPELLANT
Graphite	Burn[1]	Explosion
Strip Laminate	Detonation	Explosion
Aluminum	Detonation	Explosion
Steel	Detonation	Explosion

----
[1] = End Ring Ejected

the case but also the steel oven walls. The ignition temperature of the composite propellant was ~190°C and 2 psi (14 kPa) internal gas pressure was observed prior to ignition. Even though the ignition temperature was much higher than that of the minimum smoke propellant and the adhesive should be degraded further, the venting was not adequate to prevent the explosive response. This is consistent with Diede's work [Ref 15] which shows confinement of only 30 psi (~200 kPa)pressure can cause an explosive reaction for composite propellants in the SCO. A one pound sample of aluminized composite propellant with negligible confinement exploded violently in our SCO test. The extreme violence of AP/HTPB composite propellants under SCO conditions is probably due in large measure to the partial decomposition of the propellant, and particularly the AP, before ignition. AP is know to undergo partial decomposition generating a porous, metastable product. This phenomenon, in combination with partial decomposition of the binder, will create a porous bed that is liable to explode or undergo deflagration to detonation transition upon ignition at high temperature.

In summary, the generic motor test matrix showed substantial advantages for composite cases over monolithic metal in meeting the IM criteria. For minimum smoke propellants the response were improved in all three tests, ie; BI, FCO, and SCO. For reduced smoke propellants the responses were clearly improved for the FCO test and improvement was inferred for the BI test. The tests also confirmed the difficulty of meeting the SCO criteria, and demonstrated the violence of AP/HTPB propellants under SCO conditions.

4.2 PROPELLANTS

In the following discussion, minimum smoke and reduced smoke propellants are treated separately, since they present different problems with respect to meeting IM requirements.

4.2.1 Minimum Smoke Propellants

The principal challenge with minimum smoke propellants is to reduce the shock sensitivity while maintaining the energy density. Current slurry cast XLDB propellants have a theoretical Isp of ~248 sec and a density of ~1.69 g/cc with a card gap of 140 and a C_d of ~6.4 mm. Cast double base and polymer modified cast double base have Isp values ranging from 220 to 240+ sec and card gap values ranging from 0 to 180 depending on the composition. A great deal of work has been conducted in the U.S.A. by both DOD and industry to improve the balance of sensitivity and performance in minimum smoke propellants.[Ref. 16,6,8-11]

4.2.2 Shock Sensitivity of XLDB Minimum Smoke Propellants

The shock sensitivity of crosslinked double base propellants depends primarily on the binder energy (Hex), and nitramine content and size. It's widely recognized that reducing the size of the nitramine in a XLDB propellant reduces the shock sensitivity. This was confirmed in a recent study by Schedlbauer and Kretschner (ref 17). Herriott (ref 18) demonstrated the strong effect of HMX content on shock sensitivity by measuring the card gap values of a series of propellants in which the concentration of HMX was varied from 0

to 50% in a high energy binder (1200 cal/g Hex). Even though 4 micron HMX was used, the initiating pressure dropped from 75 to 25 kbar as the HMX increased from 0 to 50% (Figure 7). The effect of binder energy from 500 to 1200 cal/g Hex on shock sensitivity at various HMX levels is shown in Figure 8. With no HMX present, the shock sensitivity was strongly dependent on binder energy; i.e., increasing Hex from 700 to 1100 cal/g decreased the initiating shock pressure from 142 to 88 kbar, a 38% decrease. As the HMX level increased, the effect of binder energy on shock sensitivity decreased as shown in Figure 8. With 50% HMX present, increasing the binder Hex from 700 to 1100 decreased initiating pressure from 32 to 28 kbar, only a 13% decrease. In summary, solid nitramine (HMX or RDX) content and size are dominant effects on propellant shock sensitivity, followed by binder energy.

4.2.3 Shock Sensitivity of Solvent Cast Double Base Propellants

The shock sensitivity of cast double base and polymer modified cast double base propellants shows the same kind of dependence on nitramine content and size, and binder energy as the XLDB propellants described above. For instance, increasing the Hex from 700 to 1100 in an unfilled cast double base propellant increased the card gap from ~15 to ~45 (decreased the initiating pressure from 130 to 90 kb), similar to the change observed with XLDB.

Some rate modifiers, notably Pb_3O_4 strongly sensitized cast double base propellants. Addition of 3.3% of this modifier to an unfilled CDB propellant increased the card gap from 40 to 120. The incorporation of HMX-RDX to CDB-PMCDB propellants increases the shock sensitivity substantially. For example, 25% HMX in a CDB formulation with a binder Hex of 900 cal/g increases the card gap from 35 to 140. This implies that the addition of even small amounts of HMX or RDX to CDB/PMCDB propellants will result in problems with the SD, FI, and SCJ tests.

CDB and PMCDB propellants without solid nitramine can be formulated to energy levels of 233-237 s and densities of 0.056-0.057 lb/in3 (1.55-1.67 g/cc). This amounts to a loss of 12% in energy density from the XLDB Class 1.1 minimum smoke propellants currently in production. These formulations have card gap values in the range of 40-50 and C_D of 12 to 18 mm.

4.2.4 Ammonium Nitrate based Minimum Smoke Propellants

Comfort, et al (Ref 19) conducted an extensive search for alternatives to solid nitramines such as RDX or HMX that would provide comparable impulse while reducing shock sensitivity. Impulse density calculations were made for a large number of energetic materials, including both materials that are commercially available and some that are only laboratory items at present. Very few of these compounds gave propellant energies that matched those of RDX and fewer still have been produced in the pilot plant scale. The more promising compounds were evaluated in slurry crosslinked double base propellants using card gap as an index of shock sensitivity. None of these compounds gave propellants with comparable energy density and lower shock sensitivity than RDX. We are currently synthesizing new compounds that offer potential improvement in energy-sensitivity balance for evaluation in propellant.

Among the commercially available materials, ammonium nitrate, with or without phase stabilizer, offered the best balance of properties. Extensive development was carried out in which the shock sensitivity, impulse, ballistics, mechanicals, and aging of AN (or PSAN-phase stabilized ammonium nitrate) were characterized. While improvement is still needed in the areas of mechanicals and aging, a family of Class 1.3 minimum smoke propellants with an energy density 4-10% less than the current Class 1.1 propellants was achieved. Current activity is focused on tailoring these propellants to meet missile system requirements.

To optimize the energy density-sensitivity balance of minimum smoke propellants, a study of shock sensitivity was conducted as a function of binder energy, oxidizer type, concentration, and size, and plasticizer type. Card gap was used as a measure of shock sensitivity. Figure 9 shows a plot of card gap or initiating pressure versus impulse for a series of PSAN propellants in which the above parameters were varied over a wide range. To a first approximation, the card gap values were a function of the propellant energy regardless of the parameter varied. Two departures from the correlation in the direction of an improved energy-sensitivity trade are discussed below.

The nitramine particle size effect was exploited to improve the impulse-sensitivity trade. A Sweco mill was used to grind RDX to a weight median diameter of ~1.5 microns. This material could be used to replace up to 20% of the PSAN while maintaining a card gap of 65 and increasing the impulse by 4 seconds. Conversely the use of larger RDX, ~ 5 microns, resulted in an increase in the card gap to 80. While the substitution of 20% of the PSAN with the fine RDX does not increase card gap (or lower initiating pressure), it did reduce the

FIGURE 8
EFFECT OF BINDER ON THE SDT SENSITIVITY OF MINIMUM SMOKE PROPELLANTS AT VARIOUS HMX CONTENTS

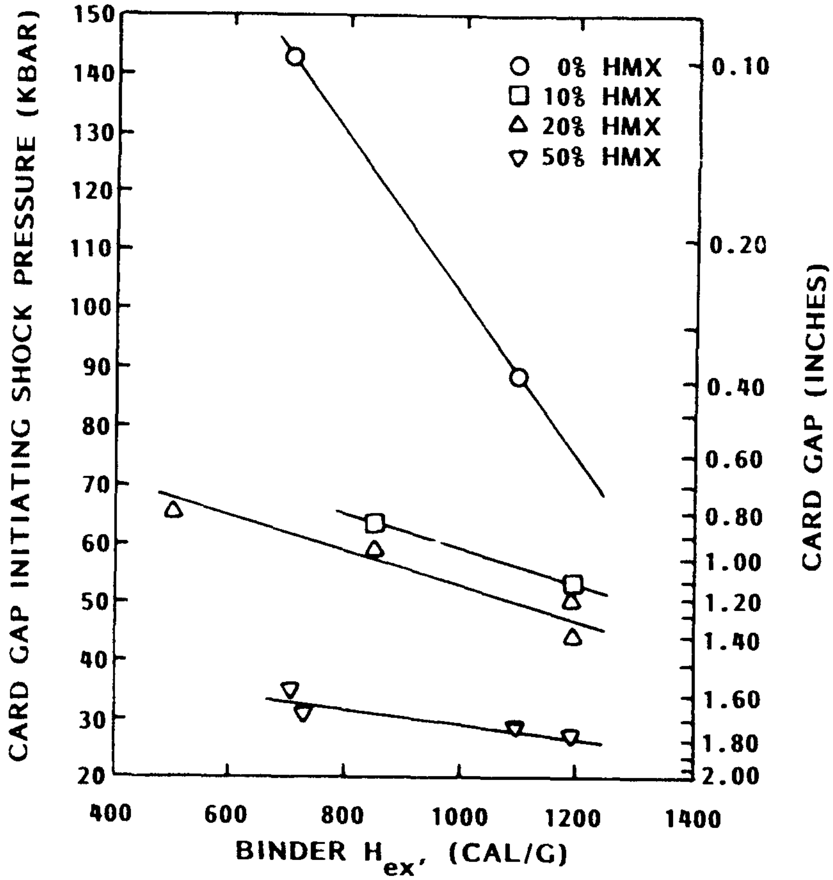
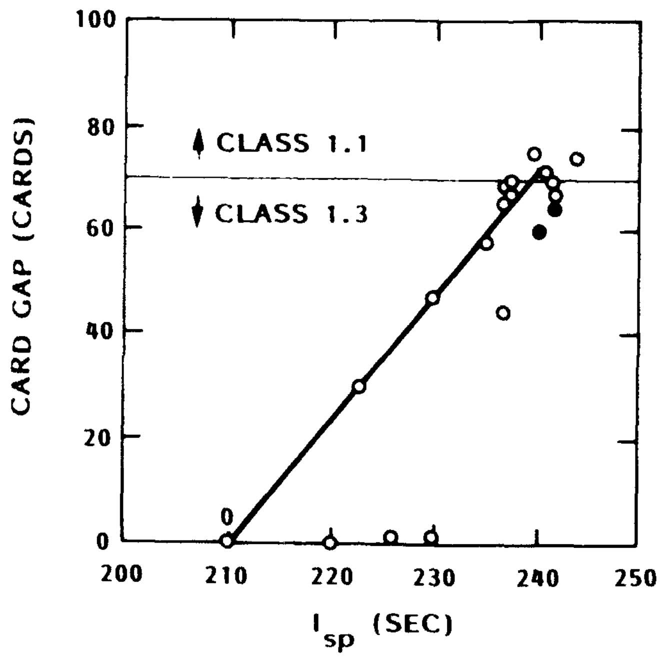


FIGURE 9
PERFORMANCE AS A FUNCTION OF SHOCK SENSITIVITY FOR CLASS 1.3 MINIMUM SMOKE PROPELLANTS



critical diameter from 20mm to 10mm. Thus, the card gap is a useful indicator of shock sensitivity but it does not provide an unequivocal means of predicting the behavior in larger scale tests-as subsequent discussion will demonstrate.

The use of an energetic nitramine polymer in combination with lower energy nitrate ester plasticizers resulted in a formulation with an improved balance of impulse and sensitivity as indicated in Figure 9. By replacing nitroglycerin with trimetholethanetrinitrate and the polyglycoladipate with a nitramine polymer, an Isp value of ~230 sec was obtained at zero cards. With the use of a similar binder and fine RDX, a card gap of 45 was obtained at 237 sec. This combination of sensitivity and energy is of interest for a number of missile systems under development.

A number of PSAN based Class 1.3 minimum smoke propellants are summarized in Table 9. The table shows formulations with card gaps values less than 70 and impulse values in the 235-240 sec range. Aging, mechanical properties, and burning rates are also given. Tailoring to improve the balance of properties is currently underway. An eight-inch diameter rocket motor with a graphite composite case was loaded with a PSAN based Class 1.3 minimum smoke propellant and successfully fired (Figure 10). This motor was fired with a laser safe-arm igniter system which will further enhance the IM characteristics of the missile by eliminating sensitive pyrotechnics from the ignition train. The delivered thrust was as predicted and represented a combustion efficiency of 99.3%.

4.2.5 Shock Sensitivity Tests in Generic Motors

Sympathetic detonation and shaped charge jet tests were conducted on Class 1.1 and two Class 1.3 minimum smoke propellants in graphite composite case generic motors (Table 10). The tests were carried out in accordance with MIL-STD-2105A; a schematic of the test arrangement for SD is shown in Figure 11. The sympathetic detonation tests were conducted with and without glass composite launch tubes (13mm in thickness) to determine their mitigation capability. The Class 1.1 propellant (64% RDX or 55% HMX) detonated both with and without the launch tube. Correspondingly, it also detonated with the 81 mm shaped charge jet. Conversely, the Class 1.3 propellant with 64% PSAN and no nitramine showed no reaction of the acceptor in the sympathetic detonation test. It also passed the SCJ test with 20% of the propellant being recovered. Although the card gap of the Class 1.3 propellant in which the PSAN was partially replaced with fine RDX (20% RDX and 44% PSAN) was essentially the same as the all PSAN formulation it did not pass either SCJ or the SD test (without launch tube). Clearly the card gap does not provide an unequivocal indicator of the missile response in the IM tests. The 20% RDX propellant did pass the SD test when protected by the glass composite launch tube. In summary the all PSAN propellant passed the SD and SCJ tests at a one inch web in a graphite composite case generic motor.

4.2.6 Composite Propellants

The efforts to provide composite propellants that meet the IM requirements have focused on improved extinguishability, milder response in slow cook-off, and tougher propellants. The approaches discussed in this paper include: 1) the use of metal perchlorate oxidizers to enhance thermal stability, 2) alternative polymeric binders that improve extinguishability and toughness. Energy density equivalent to those of the current AP/HTPB formulation can be obtained with both of these approaches.

4.2.7 Insensitive High Density Propellants

High density propellants in which the AP oxidizer was replaced with potassium perchlorate (KP) are a promising approach to meeting the IM requirements while maintaining the volumetric impulse of current rocket propellants. We have demonstrated that KP-based propellants have much better thermal stability, less sensitivity to impact, and a greater tendency to extinguish at low pressures than comparable AP-based propellants. Thermodynamic calculations have shown that the volumetric impulse of KP/A1/HTPB propellant is comparable or greater than many of the tactical rocket propellants now in production. Performance trade studies were done in which potassium, lithium and sodium perchlorate were evaluated as replacements for AP. The impulse decreases as AP is replaced by the metal perchlorates but the volumetric impulse increases as shown in Figure 12. While KP has lower performance it was selected for evaluation because lithium and sodium perchlorate are very hygroscopic which would present difficult processing problems.

A comparison of aluminized AP and KP propellants was carried out over a wide range of compositions using V_b at a mass fraction of .37 as the measure of performance. This parameter was chosen as representative of the mass fraction typical of tactical missiles. Neither impulse nor impulse-density is an accurate measure of rocket motor performance because the contribution of density depends on mass fraction. The performance of KP/A1/HTPB

FIGURE 10
CLASS 1.3 MINIMUM SMOKE PROPELLANT SUCCESSFULLY FIRED IN A COMPOSITE MOTOR WITH A LASER SAFE/ARM

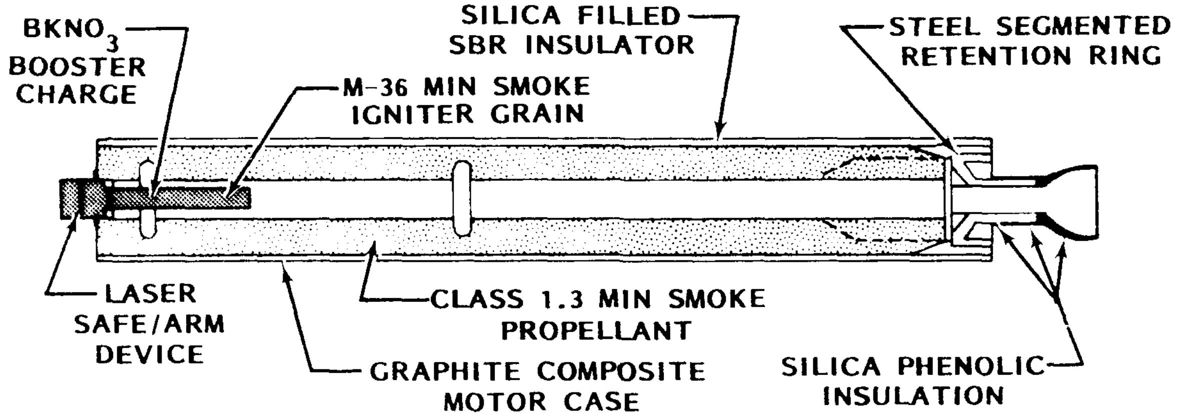


FIGURE 11
EXPERIMENTAL CONFIGURATION FOR SYMPATHETIC DETONATION TESTS

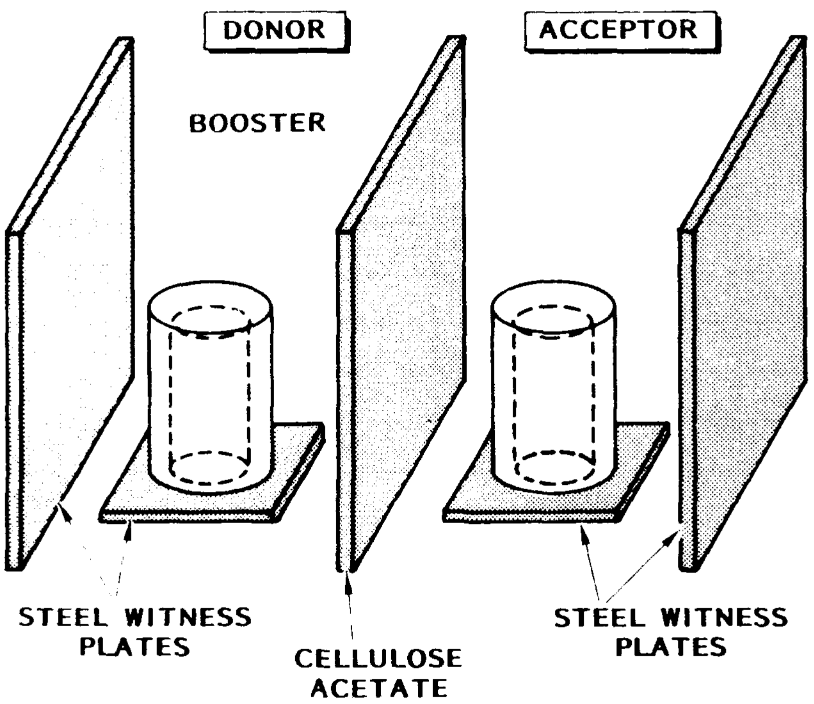


TABLE 9
BASELINE CLASS 1.3 MINIMUM SMOKE PROPELLANTS

OXIDERS POLYMER	PSAN/RDX PGA	PSAN PGA	PSAN/MOD PGA
$I^{o}sp$ (Sec)	240	236	235
Density (g/cc)	1.66	1.63	1.62
Card GAP	60	60	60
C_D(mm) Unconfined	--	45	--
Mechanicals			
E_o (MPa)	5.0	3.0	5.1
σ (MPa)	1.8	0.7	0.6
ε (%)	36	29	17
ε (%) at -45°, Ignition	19	--	14
Ballistics			
R at 1000 psi (mm/s)	6.6	6.4	12.0
Slope	0.68	0.74	0.45
Aging			
MNA Depletion at 70°C (Days)	20	53	45

TABLE 10
RESPONSE OF MIN SMOKE PROPELLANTS IN GRAPHITE CASE
GENERIC MOTORS TO IM TEST STIMULI

TEST	CLASS 1.1	CLASS 1.3	
		20% RDX	0% RDX
Bullet Impact	No Reaction	--	No Reaction
Fast Cook-Off	Burn	--	Burn
Sympathetic Detonation			
Without Launch Tube	Detonation	Detonation	No Reaction
With Launch Tube	Detonation	No Detonation	No Reaction[1]
Shaped Charge	Detonation	Detonation	No Detonation
Slow Cook-Off	Burn[2]	Burn[2]	Burn[2]

1 = By Analogy
2 = End Ring Ejection Followed by Burning Reaction

propellant optimized at approximately 67% AP, 24% Al and 9% binder and gave a V_b within 2% of a high performance AP/Al/HTPB (70/21/9%) propellant. For instance, the theoretical burnout velocity of the KP propellant was 1.22 km/s compared to 1.24 km/s for the AP propellant. The properties of KP and AP composite propellants are compared in Table 11. The comparison was made in 88% solids HTPB propellant with 70% oxidizer and 18% Al. As Table 11 shows, the KP propellant had several advantages over the AP composition: improved thermal stability, reduced initiation sensitivity and higher strain capability. These characteristics plus the tendency of the KP-based propellants to extinguish at low pressures should result in a mild response to the bullet impact and fragment tests. The improved thermal stability and the elimination of porosity produced by the low temperature decomposition of AP should result in a less violent response in the slow cook-off test. Slow cook-off tests on the laboratory scale have confirmed this prediction; ie., no ignition at 500°C with a 50 g sample and a burn with a one pound sample at 300°C. A ten-pound generic motor survived a slow cook-off test to 232°C without ignition. After 24 hours at that temperature it was cooled to ambient and ignited - the burn was normal.

Development work continues on this family of propellants; they are particularly suited to missiles that require high performance aluminized propellants. Due to the formation of KCl in the exhaust, this formulation is useful only in missions where signature is not a critical issue.

4.2.8 Extinguishable Propellants

The use of alternative binders to HTPB, generally polyethers or polyesters that enhance toughness and extinguishability is being explored [Ref 20-22]. Reed and coworkers have demonstrated an order of magnitude increase in toughness using a polyakylene oxide binder, making the propellant very resistant to damage from bullet or fragment impact. Using a similar binder, we have independently developed a family of propellants with significant advantages over HTPB propellants. Of particular importance for IM is the improved extinguishability and much lower susceptibility to electrostatic initiation. A milder response to bullet impact was demonstrated in both steel and graphite composite cases. Other propellant characteristics that are critical to the development of an efficient rocket motor also compare favorably with those of HTPB. For instance, these

TABLE 11
KP PROPELLANTS POSSESS FAVORABLE PROPERTIES

COMPOSITION	CONTROL	HIGH DENSITY
AP	70	0
KP	0	70
Al	18	18
Polymer (HTPB)	8.4	8.4
I^o_{sp}	260	229
$I^o_{sp} \cdot \rho$	16.9	17.[illegible]
Eo (MPa)	6.5	5.5
ε (%)	23	48
σ (MPa)	1.1	1.2
IMPACT (cm)	21	41
FRICTION (lb @ ft/sec)	160/3	385/3

FIGURE 12
IMPULSE AND VOLUMETRIC IMPULSE AS A FUNCTION OF CO-OXIDIZER
CONCENTRATION IN ALUMINIZED COMPOSITE PROPELLANTS

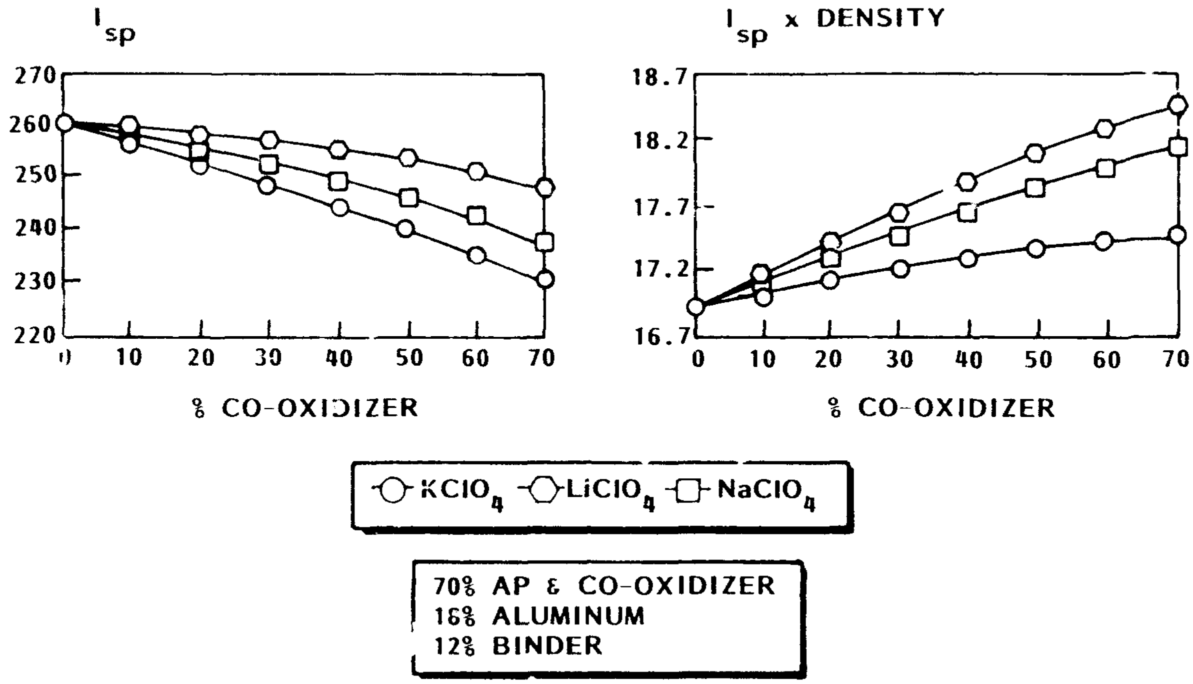
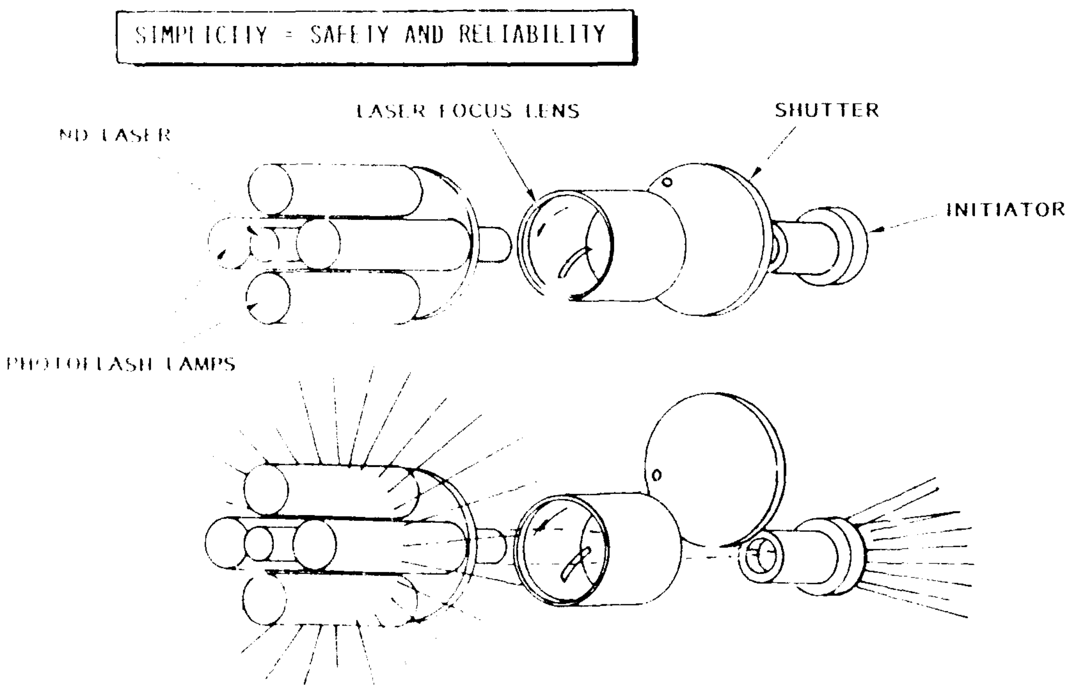


FIGURE 13
LASER ARM/FIRE CONCEPT



propellants show an increase in impulse density while maintaining burning rate range, mechanical properties, and cost. This family of propellants is applicable to a wide range of tactical missiles, either those requiring reduced smoke or high performance aluminized propellants. Further development, including tailoring of mechanical and ballistic properties, processing studies, and larger scale IM testing is being carried out at present.

4.3 NEW INGREDIENTS

New ingredients are needed to meet the IM standards while maintaining the energy density levels of current Class 1.1 minimum smoke propellants as shown in the preceding section. A widespread effort in the NATO countries and elsewhere is underway to develop and characterize these compounds (Ref. 23-27). The effort is a comprehensive one, in that new energetic plasticizers, polymers and oxidizers are being sought. While many promising compounds have been identified and synthesized, none have yet been demonstrated that allow the formulation of an insensitive minimum smoke propellant that matches the performance and other requirements of current production propellants. A dedicated, long term effort will be required to scale-up and use these materials in deployed missiles.

4.4 ROCKET MOTOR CASES

We are evaluating the major case construction materials for their effect on the response to the IM stimuli. As the discussion on testing showed the effects are substantial. The relative contributions of the various materials in mitigating the BI, SCO, FCO and ESD hazards are shown in Table 12. The benefit of the case in mitigating the hazard is assessed on two levels: either a dominant or contributory effect. As the Table indicates the graphite-epoxy case offers some mitigating capability over the widest range of threats. Considered in combination with its excellent strength to weight ratio the IM benefits make composite cases a strong candidate for future tactical rocket motors.

4.5 LASER SAFE/ARM SYSTEM

Hercules has developed a laser safe-arm system that eliminates the need for sensitive pyrotechnic materials such as lead azide or lead styphanate. The laser concept is a simple approach to arm fire systems as illustrated in Figure 13. Photoflash lamps are used to generate the laser pulse from a neodymium doped glass rod. The pulse is focused on the igniter material or a fiber optic cable with a convex lens. A simple shutter serves as the safing device. This concept has been reduced to practice

TABLE 12
MAJOR MUNITIONS HAZARDS CAN BE MITIGATED BY CASE MATERIAL

CASE MATERIAL	FCO	SCO	BI	ESD
Steel				X
Aluminum	X			X
Strip Laminate	X		C	X
Glass/Epoxy	X	C	C	
Aramid/Epoxy	X	C	C	
Graphite/Epoxy	X	C	C	X
Hybrid	X			X

X = Dominant Effect
C = Contributory Effect

in a number of systems and the resulting laser arm fire potentially effective against bullet impact since it does devices have substantial advantages over conventional electromechanical devices:

Greater reliability
Lower cost
Less weight
No electrical connection to the initiator
Reduced sensitivity to electromagnetic radiation

Six photoflash lamps generate 2 joules with a pulse half width of 35ms, which is more than adequate to ignite typical initiator materials such as $BKNO_3$. In general, the output from 2 lamps is sufficient to initiate $BKNO_3$. Hence the lamps are wired in two independent circuits to provide redundancy. The laser system is readily adaptable to remote and/or simultaneous initiation of propellant charges through the use of fiber optic cables. The loss in energy upon transmission through fiber optic cables is negligible, allowing the laser to be located on the launch platform or on the missile at a location remote from the igniter. The high energy output also makes it possible to split the pulse into multiple cables and simultaneously ignite separate charges.

Drop-in laser safe-arm units that replace the electromechanical devices for Sparrow have been built and successfully tested according to the qualification specifications. They have also been adapted to and demonstrated in the following applications:

Surface and air launched rocket motors, HVM, Sparrow
Multi-pulse rocket motors
Aircraft ejection seats (F-16)
Gun Launched Rocket Motors
120 mm gun system

All of the requirements of MIL-STD-1512 and MIL-I-23695 were met by the laser safe-arm system. The laser safe-arm device is a promising method to reduce the sensitivity of missiles while improving reliability, reducing weight and cost.

4.6 INSENSITIVE MUNITIONS MODELING

There is widespread activity in developing models to predict the response of munitions to the energetic stimuli identified by MIL-STD-2105A [Ref 27-30]. Accurate models are needed to greatly reduce test costs and provide guidance for selection of sound approaches. Victor has reviewed this area in considerable detail [Ref 4]. Our program is currently focused on the investigation of: slow cook-off model and experimental diagnostics, molecular model for sensitivity prediction and bullet impact model. These projects will provide understanding and guidelines for the development of insensitive tactical missiles.

5.0 ACKNOWLEDGEMENTS

Many have contributed to the work described in this paper. I would like to acknowledge the contributions of Dr. A. A. DeFusco, Dr. R. W. Naylor, Dr. G. E. Herriott, Dr. T. F. Comfort, Mr. J. H. Rice, Jr., Mr. F. Beavers and Mr. A. G. Butcher. I also appreciate the support of Mr. J. F. Hixon.

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Discussion

QUESTION BY COLE, CANADA: How much gas venting is required to get HTPB/AP propellant filled motors to pass the slow-cook off test?

ANSWER: One China Lake test with controlled blow out disks found that the case "back pressure" needed to be reduced to 30 psi or less in order to pass. In another test of a Sidewinder motor with both ends open, the motor failed. They believe the problem in that instance is related to the high L/D ratio of the motor.

QUESTION BY HELD, FRG: What was the diameter of the shaped charge used and the diameter of your GAP tests?

ANSWER: The diameter for the shaped charge jet is 81 mm. The standard card GAP test was used; ~1.5 inches internal diameter and ~2.0 inches outside diameter steel pipe loaded with propellant.

HAZARDS OF ENERGETIC MATERIALS AND THEIR RELATION TO MUNITIONS SURVIVABILITY

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ABSTRACT

Activities of the Technical Cooperation Program (TTCP) W Action Group 11 (WAG-11) on "Hazards of Energetic Materials and their Relation to Munitions Survivability" are described. The concept and uses of hazard assessment protocols are presented.

1. INTRODUCTION

This paper describes activities of many scientists from Australia, Canada, the United Kingdom, and the United States. The five listed "authors" of this paper are the national leaders of this effort, and the reader must recognize that the work presented in this paper is the work of many scientists and engineers, not just the listed authors. Space considerations preclude listing all of the contributors in this paper. These many scientists and engineers have been meeting since the beginning of 1987 to discuss the response of munitions to bullet/fragment impact, electrostatic discharge, shaped charge jet impingement, cook-off, and sympathetic detonation. At the first meeting, the members reached consensus that a program leading to mechanistic understanding of reactions and predictive capability of outcome(s) was required. It was felt that traditional, standard go/no-go tests did not provide this understanding nor the predictive capability. During the various discussions a general approach evolved. From general discussions of stimulus, sample, environment leading to some response we found ourselves presenting classes of output (detonation, explosion, burning, no reaction) in terms of input stimulus and target (includes sample and environment). This determination of hazard responses of the target munition as a function of a wide variety of stimuli (for example, those combinations of fragment mass, fragment velocity and fragment shape leading to detonation, those combinations leading to explosion, and those combinations leading to no reaction) could lead to hazard assessment/response plots for a given munition. These hazard assessment/response plots could be compared to the specific fragment masses, velocities, and shapes for a given threat (e.g., warhead) to determine the likely response of a given munition to a given threat(s). As will be shown in this paper, this optimistic desire has been achieved in many of the hazard areas.

It was also decided that rather than having several single workshops, it made sense to have sequential workshops on bullet impact, fragment impact, shaped charge jet impact, and sympathetic detonation all at the same meeting since there is significant technical overlap between the areas. For example all of these areas must be concerned with prompt shock to detonation reactions. This "omnibus" meeting was held in July 1988 at the Royal Armament Research & Development Establishment (RARDE), Fort Halstead, the United Kingdom. A workshop on Electrostatic Discharge was also held concurrently at RARDE, Waltham Abbey, the United Kingdom. This workshop was scheduled because of the great progress that was being made in this area. The two groups convened at RARDE Fort Halstead on July 8, 1988, and presented the summary of their workshop findings to the National Leaders. Besides technical exchange, the major output was the establishment of collaborative efforts between nations.

The hazard assessment plots are the output of the hazard assessment protocol method applied to the hazard areas listed above. What is a hazard assessment protocol? It is an ordered procedure that results in a flow chart that directs the user through the consideration of a hazard area. This consideration will be of his sample in its environment subject to the threat stimuli he thinks the sample will encounter. The hazard assessment protocol helps tell the designer and test personnel (1) what paths are most likely to be encountered, and hence must be considered, and (2) what information must be obtained in order to perform the assessment. Because the assessment is based on logic and directly associated with the ordnance item in a real environment and subject to real threats, it has more value than the results of a few go/no-go hazard tests. The protocol approach is intended to be (1) a design tool used early in the design cycle to anticipate potential hazard problems, and (2) an aid to program personnel to mitigate existing munition hazard problems. The protocol approach has been described and used in Refs. 1 and 2.

Perhaps it is easier to understand the protocol approach by working through a simplified example: impact of a fragment on an idealized munition consisting of a case wall-energetic fill-case wall. There are several possible reactions as illustrated in Fig. 1. The first consideration is the prompt shock to detonation. In this situation the fragment impacts the munition, sending a shock wave into the cased energetic material. This shock wave transitions into a detonation. If the fragment does not impart sufficient energy to cause a detonation, we may still have a significant problem resulting from the fragment penetrating the case. If the fragment penetrates several possibilities are likely to occur. The worst is that the fragment ignites the energetic material and the combustion rapidly produces gases that can't be vented quickly. In this instance the munition may violently explode sending large fragments at modest to high velocities. Another situation that often occurs, often with less severe consequences, is the fragment because of its high velocity and/or large mass, either penetrates directly through the munition and doesn't ignite the energetic material and/or provides an extremely large vent or breaks open the case. In these instances, a fire may ensue but at least there was no detonation or explosion. The last instance, and the most desired, is that the fragment simply hits the case and bounces/ricochets off causing no reaction.

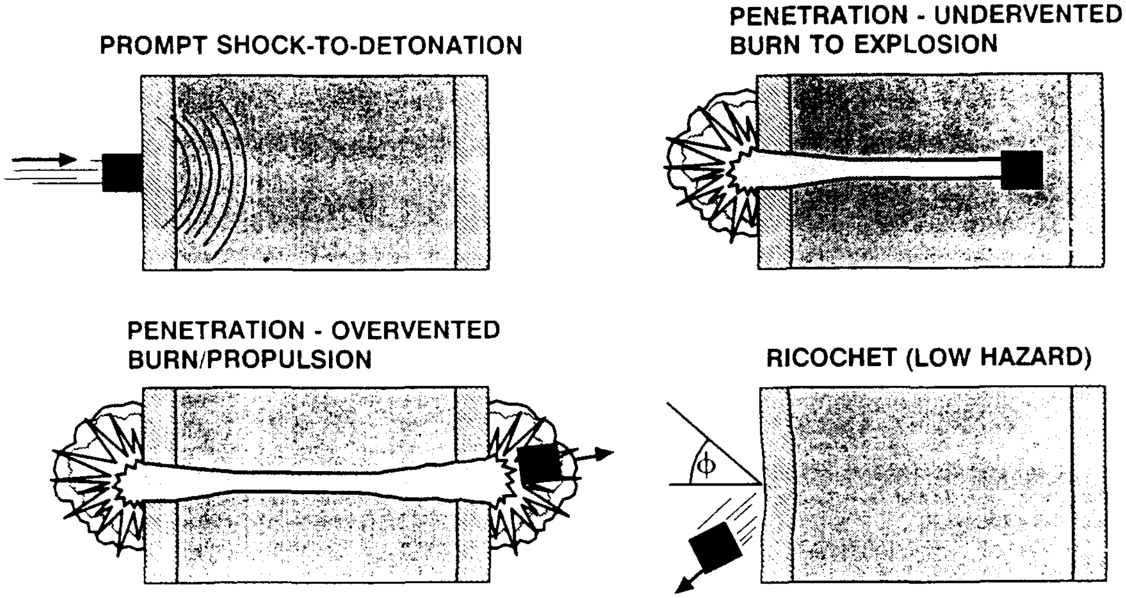

Fig. 1. Possible Reactions When a Fragment Impacts a Cased Energetic Material.

Which reaction is likely to occur? That's where the protocol comes in. Let's take a simplified look at this problem. Our first concern was: "Do we get a prompt shock to detonation?" The protocol path of Fig. 2 addresses this concern. We first start with the fragment having mass, velocity, size/shape, and orientation; and let's say that this is the first fragment impacting the munition. The first question to ask is how does the diameter of the fragment compare to the critical diameter of the energetic propellant (or explosive). The critical diameter is the smallest diameter that will sustain a detonation. If the fragment diameter is much less that the critical diameter of the energetic material then a prompt shock to detonation transition is unlikely (however other mechanisms such as deflagration to detonation transition may be possible) and one should proceed to penetration considerations.

If however the fragment diameter is approximately equal to or bigger than the critical diameter, a prompt shock to detonation may ensue; and one must compare the shock pressure imparted by the impact to the initiation pressure required to cause detonation. If the imparted pressure is below the threshold, prompt shock to detonation is unlikely (but again other detonation mechanisms may occur - DDT, XDT).

If however the imparted pressure is above the threshold, a detonation is very likely and we must compare the web thickness to the run distance. Do we have enough energetic material to allow the shock wave to build to a detonation? Unfortunately usually if we have a small enough critical diameter and a low enough threshold, we also have a small enough run distance that a detonation is extremely probable, and it's back to the drawing board or time to consider mitigation devices or start thinking up clever arguments why a waiver should be granted.

THIS A SIMPLIFIED EXAMPLE OF PROMPT SHOCK TO DETONATION TRANSITION PATH OF FRAGMENT IMPACT HAZARD ANALYSIS PROTOCOL

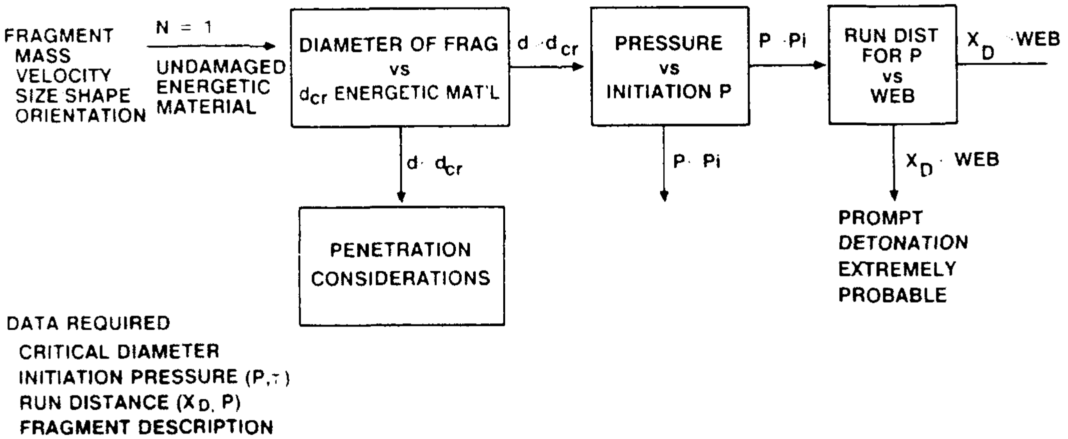

Fig. 2. Simplified Hazard Assessment Protocol for Prompt Shock Induced Detonation of a Cased Energetic Material Subject to Fragment Impact.

Even if you come through this path relatively unscathed, you may have to go through it again, this time with damaged energetic fill. The damage can come from many sources: handling, age, hit by previous fragment, etc. Now you must go through the path, but this time with the values for damaged material. The damaged materials are usually more sensitive than their undamaged counterpart. For example, 1% voids can cause the initiation pressure to drop from 40 kbars to 20 kbars (Ref. 3).

Before leaving this path, let's think about what data are required for the assessment. We need the critical diameter, the initiation pressure threshold (as a function of time), the run distance (as a function of pressure) of the undamaged and damaged energetic material, as well as the description of the fragment. Reference 2 discusses techniques for obtaining these data.

If there is no prompt shock to detonation, we still must be concerned with the penetration effects [Note: we consider SDT first because (1) it is usually the worst reaction, and (2) if it's going to occur it will be the first (and last) occurrence, taking place in microseconds, for that munition.] In the penetration path, Fig. 3, we are first concerned with whether the fragment can penetrate the case, that is, is there sufficient mass and velocity of the projectile to exceed the ballistic limit of the case. If not, we have the desired bounce-off/ricochet. However if the mass and velocity exceed the ballistic limit, we must ascertain by how much. If the mass and velocity greatly exceed the ballistic limit, the fragment may pass through the munition without igniting the energetic material and/or over-venting the case.

But if the mass and velocity don't greatly exceed the ballistic limit, e.g., the fragment lodges within the grain, we must ask if ignition occurs. If no, that's desirable. If yes, then we need to know the burn rate, burn area, pressure and vent size (not independent parameters) in order to determine if we can vent the products fast enough or whether an explosion is probable. If we can vent, we still have a fire problem to contend with. If the products are not vented fast enough an explosion can occur and the explosion can lead to other sympathetic reaction of adjacent stores - up to and including sympathetic detonation.

To predict likely reactions in this path, we must know the ballistic limit of the case, the mechanical properties of the energetic material, deformation of the fragment, ignitability of the energetic material, burn rate, and burn area of the energetic material, as well as case confinement and venting.

This is a simplified example. The current protocol is on a 2 foot by 3 foot chart and is described in several pages of text. Before dismissing this as being unwieldy, the reader must be cautioned that (1) while the protocol considers all the paths, the user doesn't "go down" all the paths, (2) the responses that the user gives direct him through the path appropriate to his situation, and (3) the protocol is being put into user-friendly, personal computer compatible software. At present it is easy to use and when the software is complete it will be even easier to use.

Once you have these data, what do you do with them? The data can be used to construct a hazard assessment plot shown in Fig. 4. Starting at the right hand of this figure, we first determine what combinations of projectile mass-velocity will cause prompt detonation. This region is ameliorated at the lower values of mass (smaller diameters) by critical diameter considerations (for a more complete discussion of critical diameter effects, please consult pg. 140 of Ref. 2). Also shown on Fig. 4 are the ballistic limit lines for the case (B.L. is the single ballistic limit line, while 2 B.L. is the ballistic limit for penetrating one side and emerging through the second side.). Somewhere between/near these lines is the explosion phenomena (sometimes referred to as burn to violent reaction, or BVR for short). The region to the left of the ballistic limit line is the bounce-off/ricochet zone, while the region to the right of the explosion region and to the left of the detonation region is the zone of over-vented reactions.

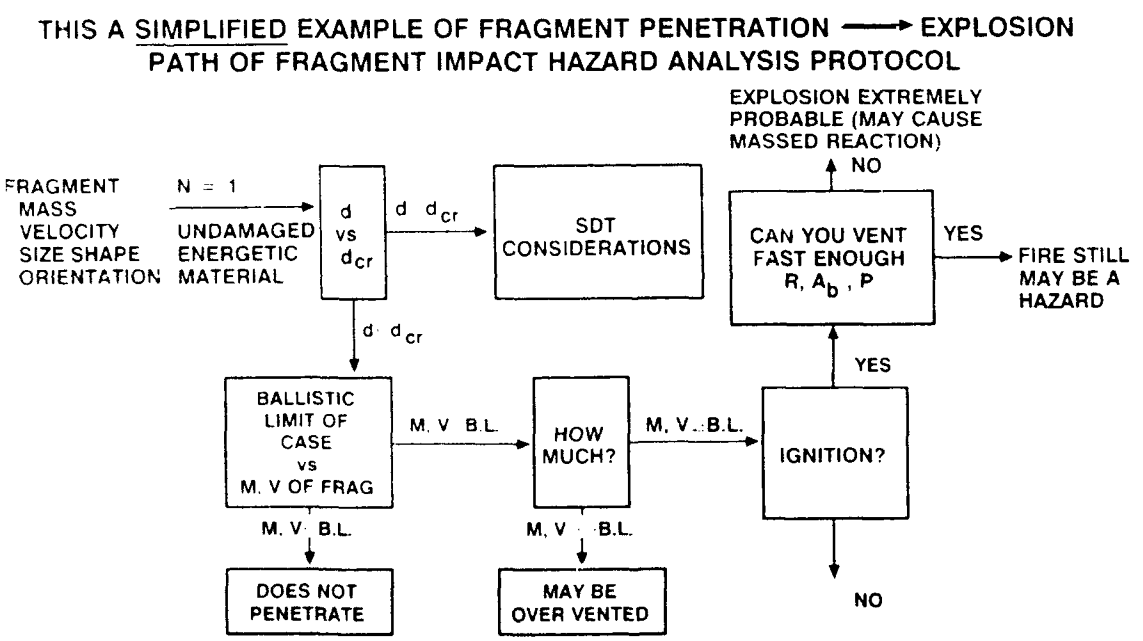

Fig. 3. Simplified Hazard Assessment Protocol for Fragment Impact/Penetration of a Cased Energetic Material.

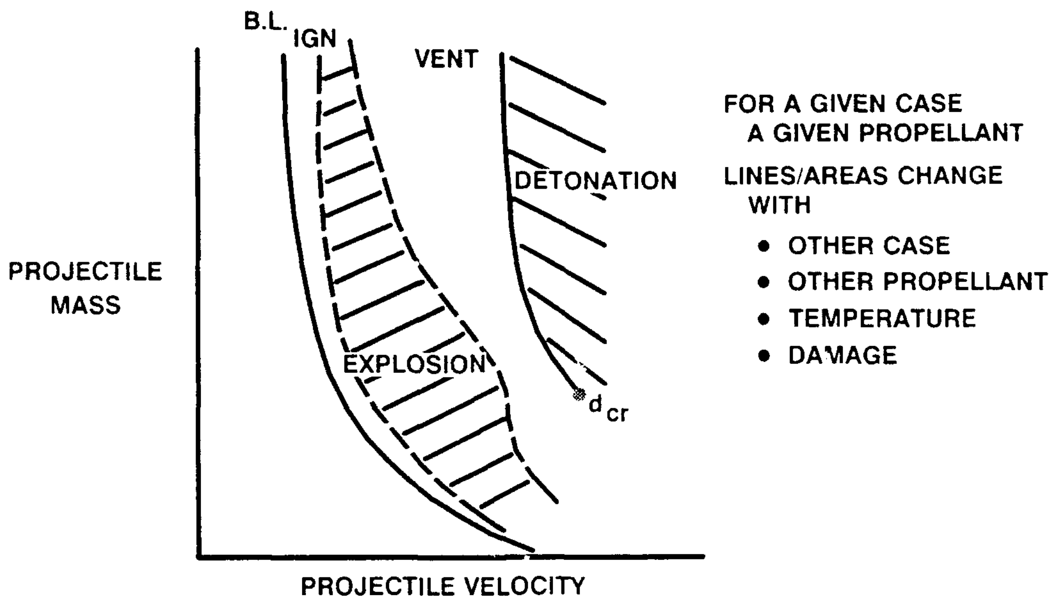

Fig. 4. Hazard Assessment Plot for Fragment Impact of a Cased Energetic Material.

The actual locations of such lines on a hazard assessment plot are going to be dependent on the various munition designs, the environment, and the threat stimuli, and will change as you change the design, the environment, and the stimuli. The point to be made here is that one of our goals has been met: you can predict the hazard response, based on laboratory and small-scale field tests, early in the design cycle, and then if you experience an unwanted response, see the effects of design changes. This will be more clear below.

While the cartoon of Fig. 4 shows the overvented zone, in reality at present we have difficulty predicting the exact location of this zone. We know it exists and have specific examples of when it exists for given munitions and given threats, it's just that we have difficulty in a priori prediction. So instead of the hazard plot of Fig. 4, we use the semi-logarithmic plot of Fig. 5. [This is an actual plot for a given ordnance item.] Here the three areas (prompt detonation, burn to violent reaction, and ricochet) are shown and one can see the general vulnerabilities of this particular munition.

While knowledge of a munition's vulnerability is very desirable, it can be extended to determine the vulnerability of the munition to a specific threat such as detonation of an enemy warhead or detonation of one of our own warheads (sympathetic detonation). To do this we need a mapping of the threat fragments.

Figure 6 presents such a threat spectrum overlaid on the hazard map of Fig. 5. The circles show the various fragments in terms of their mass and velocity. The size of the circle is indicative of the approximate number of fragments having that mass and velocity (1, 10, 100, 1000).

This overlay plot is obviously very valuable in showing the vulnerability of one munition to another. In the example given in Fig. 6, there are many fragments over 1000 grains with a velocity of approximately 6800 ft/sec. [Note: There are 7000 grains/lb. A 1/2 x 1/2 x 1/2 inch cube of steel is approximately 250 grains.] Similarly there are several fragments of 6600 grains (almost a pound each) with a velocity of 4200 ft/sec. These are obviously in the prompt shock to detonation region and represent a serious problem that must be designed away or mitigated.

Also shown on Fig. 6 by the square symbol is the standard U.S. insensitive munition fragment test fragment (250 grains and 8300 ft/sec). Obviously this test would say that there was not a prompt shock to detonation problem, although the munition would fail the test due to explosion.

Once you know that you're in trouble, plots can be used to help get you out of trouble. Figure 7 shows the effect of using various steel barriers in mitigating the impact of the two fragments discussed previously. For example, 1/4 inch thick steel barriers will move the 1140 grain fragments out of the detonation region and approximately 3/4 inch thick steel barriers will move the effects of these fragments, not only out of the detonation region, but out of the burn to violent reaction region.

Protocols exist in all of the areas. Reference 2 presents several protocols that have since been improved upon. The hazard analysis protocol for electrostatic discharge (ESD) is not only found in Ref. 2, but an improved upon ESD protocol may be found in Ref. 4. The cook-off protocol developed by this group differs from that presented in Ref. 2, and will be published in an open forum in the future. As mentioned earlier, the protocol for bullet/fragment impact is well developed, significantly past that of Ref. 2, and will be presented in open forum in the near future. The shaped charge jet protocol is also well advanced. Discussions are currently underway as to whether this protocol could be merged with bullet/fragment protocol. In the area of sympathetic reaction, there are three major diversions: (1) one donor on one acceptor, (2) one donor on multiple acceptors (stack), and (3) stack donor on stack acceptor(s).

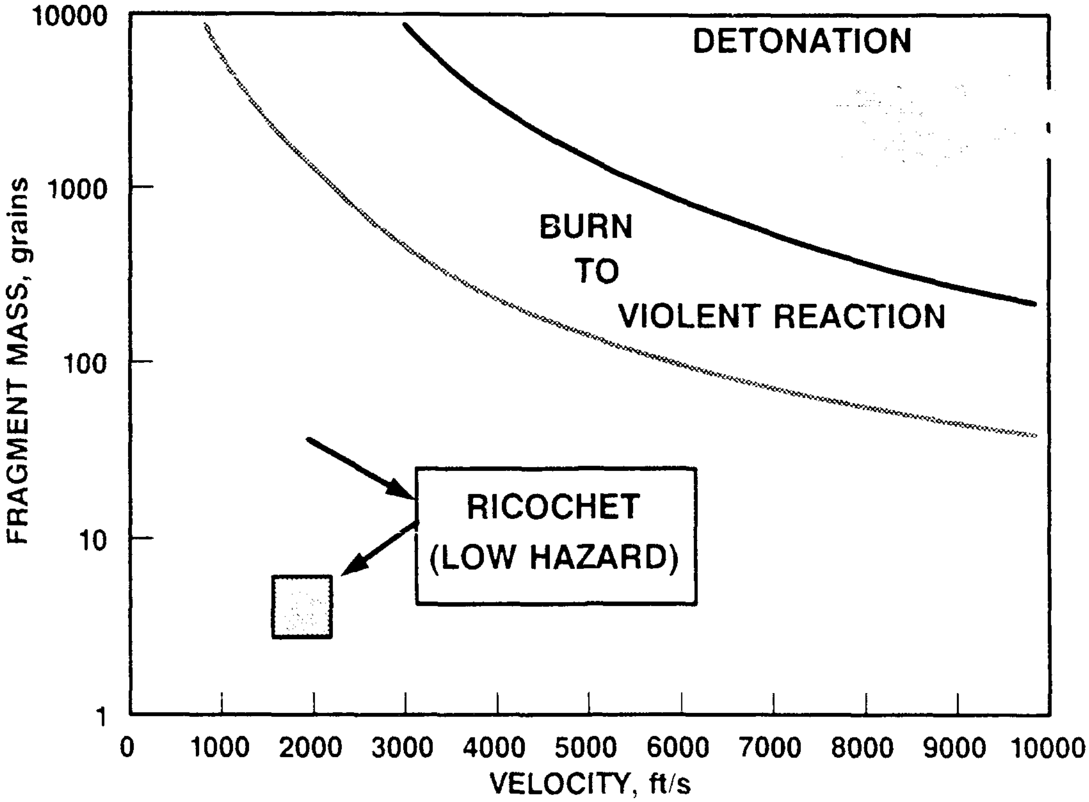

Fig. 5. Hazard Assessment/Response Plot of Fragment Impact of an Actual Munition Component.

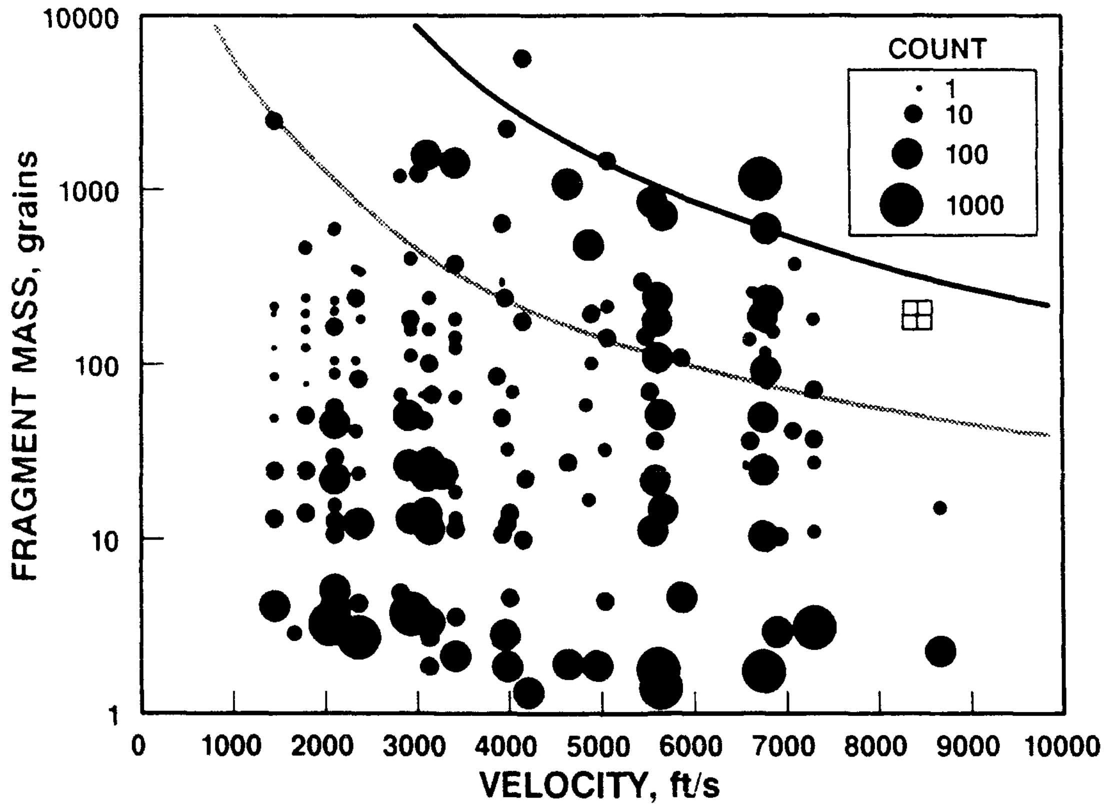

Fig. 6. Overlay of Actual Fragment Distribution (the Size of Circle Denotes Approximate Number of Fragments: 1, 10, 100, 1000) From Threat Warhead Overlaid on Hazard Assessment/Response Plot of Fig. 5.

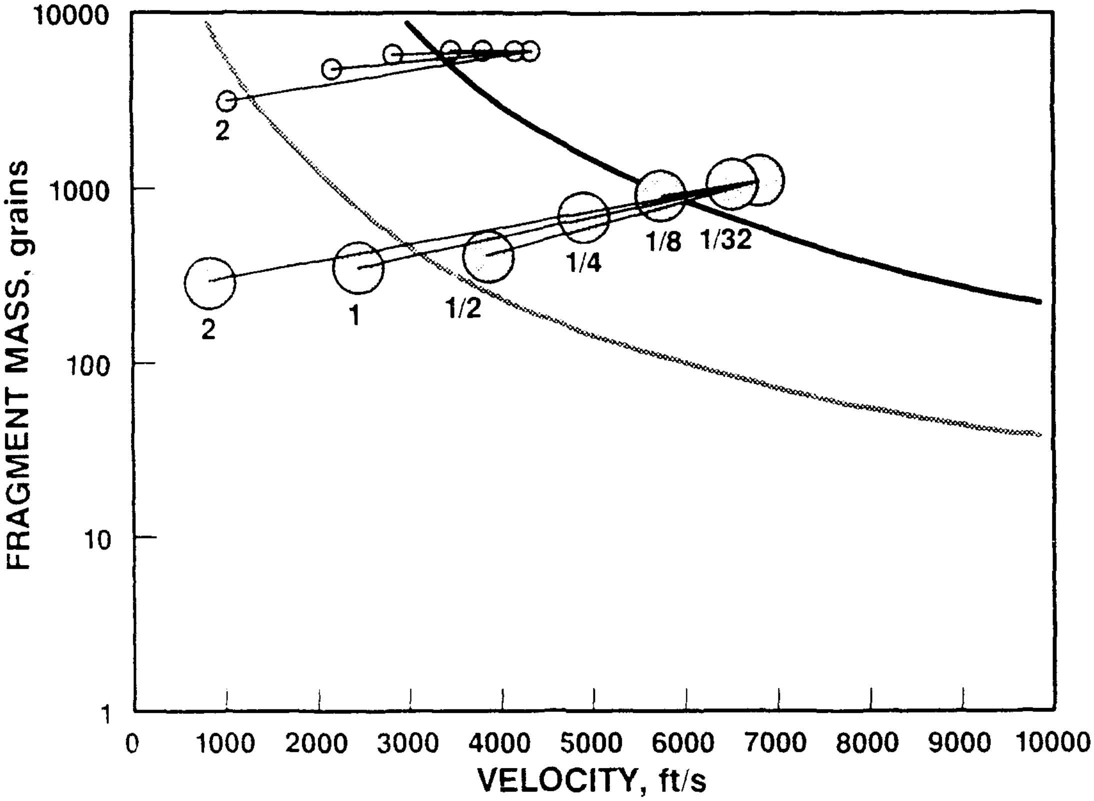

Fig. 7. Effect of Placing Different Thicknesses (in inches) of Steel Barrier Between Threat and Acceptor Munitions. [Thor equations used in this example.]

Within each of these divisions, one has to worry about spacing: (1) no space - straight shock transmission, (2) close spacing - distance between rounds less than 1/2 diameter of round and transmission mechanism is primarily "case slap," (3) intermediate spacing - fragments are forming but not completely formed, more strip-like, and (4) large separation - greater than 2 charge diameters - these are fully developed fragments. Instance 4 can be handled by the fragment protocol, as can be instance 3, if one remembers that the impactor is a "strip of fragments."

2. SUMMARY

The purpose of this paper has been to present recent activities using the hazard assessment protocol method, and to show how this method can be used. The example given in this paper has been for fragment impact; showing how hazard assessment/response plots can be created, and how specific threat maps may be overlaid to determine problem areas. Also shown was how to use these overlaid plots to determine effectiveness of mitigation efforts.

These efforts are continually evolving at a rapid rate, and readers are encouraged to contact the various "authors" with comments and suggestions.

3. REFERENCES

1. T. L. Boggs, A. I. Atwood, K. J. Graham, A. H. Lepie, C. F. Price, H. P. Richter, and D. E. Zurn. "Hazards of Solid Rocket Propellants," Proceedings of the Eastern States Combustion Institute - Physical and Chemical Processes in Combustion, Philadelphia PA, November 1985.

2. T. L. Boggs and R. L. Derr (Editors). "Hazard Studies for Solid Propellant Rocket Motors," NATO Advisory Group for Aerospace Research and Development, AGARDograph No. 316, September 1990.

3. T. L. Boggs, C. F. Price, H. P. Richter, A. I. Atwood, A. H. Lepie, N. G. Zwierzchowski, and L. R. Boyer. "Detonation of Undamaged and Damaged Energetic Materials, 19th International ICT Conference, 1988, pp. 30-1 to 30-13.

4. J. Covino and F. Hudson. "Assessment Methodology for Electrostatic Discharge (ESD) Hazards of Energetic Materials," AIAA Journal of Propulsion and Power, March-April 1991 (in press).

Discussion

QUESTION BY MAY, US: Would you please clarify your reservations about cook-off tests. Are you referring to both slow and fast cook-off tests?

ANSWER: As described in the text, and the presentation, the emphasis of TTCP WAG-11 has been on mechanistic understanding so that we can have predictive capability. That is, we understand the hazard situation so that we can apply our knowledge to predict hazard responses for given stimulus + environment + sample situations. My reservation about most large scale cook-off tests, both fast and slow, is that they are go/no-go tests that do not yield mechanistic understanding leading to predictive capability. While go/no-go tests are important to demonstrate successful compliance with IM requirements, they are inadequate in and of themselves since they are not very well instrumented, are very costly for the information derived, have poor statistical certainty and since they occur near the end of the development cycle, and the "fixes" are likely to be costly.

QUESTION BY DEFOURNEAUX, NIMIC: Thank you very much for your faith in NIMIC. All models I have seen, including yours, for bullet impact assumes the bullet stays stable. A test in France showed a bullet was stable when it entered a propellant grain and then tumbled, however there was no reaction. But in most tests there is a reaction and you cannot tell if the bullet tumbled or stayed stable. What is the value of the test if you do not know how the bullet behaves on each test?

ANSWER: That's a very good point to bring up, tests on inert material does show that bullets do tumble. Therefore, the test is a valid test whether or not the bullet tumbles.

COMPORTEMENT DES CHARGEMENTS DE PROPERGOLS A L'IMPACT DE BALLES

BULLET IMPACT BEHAVIOR OF SOLID PROPELLANT GRAINS

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Résumé

Les études de vulnérabilité sont très importantes pour le développement des propulseurs utilisant des propergols discrets énergétiques. Parmi les agressions retenues, l'impact par balles est une épreuve bien connue étudiée depuis de nombreuses années.

Toutefois, au cours de nos expérimentations sur propulseurs réels, les scénarii traditionnels élaborés pour cette agression ont été mis en défaut. Un nouveau scénario a dû être imaginé et validé pour rendre compte de ce phénomène. Le scénario met en avant le rôle joué par le propergol mais aussi de façon fondamentale par la conception du moteur (chargement + structure).

L'exposé présente les travaux expérimentaux et décrit la physique du phénomène en s'appuyant sur les travaux de modélisation qui ont été associés. Il explique l'influence de certains paramètres comme la température et la nature de la structure.

Summary

Vulnerability studies are very important for rocket motors development using high energy and minimum smoke solid propellant. Among the treated threats, the bullet impact is a well known test studied for many years

Nevertheless, during our experimentations against true rocket motor, the well-known scenarios failed. A new scenario has been identified and confirmed to take into account the new phenomenon. This scenario implies the solid propellant but also the design of the rocket motor (propellant grain + case).

The communication presents the experimental works and describes the physics of the phenomenon supported by the associated modelisation studies. It explains the influence of some parameters like temperature and nature of the structure.

INTRODUCTION

L'impact de balle 12,7 P est, parmi les agressions de vulnérabilité, une des plus retenues. La réponse des chargements de propergols à cette agression peut s'étendre dans une large gamme qui va de la non réaction jusqu'à la réaction très violente en passant par des combustions ou des éclatements plus ou moins violents. En tant que réaction très violente, la détonation est envisagée soit directe pour des propergols très sensibles au choc ou suite à une transition à partir de la déflagration pour des propergols dangereusement fragmentables. Lors du développement de propulseurs utilisant des propergols discrets, énergétiques, ces deux scénarii sont pris en compte et maitrisés.

A la suite de la détonation retardée d'un propulseur échelle 1 lors d'un tir à la balle 12,7 mm perforante à 1127 m/s en 1987, des études de compréhension du phénomène ont été réalisées. Cette analyse a montré que nous devions considérer un nouveau scénario prenant en compte la présence d'un canal dans le bloc de propergol (1),(2).

Comme l'a montré la modélisation qui a été réalisée, ce scénario met en jeu un phénomène de type XDT dans la partie arrière du chargement. Ceci est d'ailleurs confirmé par le fait que ce scénario est comme la XDT sensible à la géométrie, la température et les propriétés mécaniques.

Les essais de compréhension réalisés et les modélisations associées sont présentés dans les chapitres suivants.

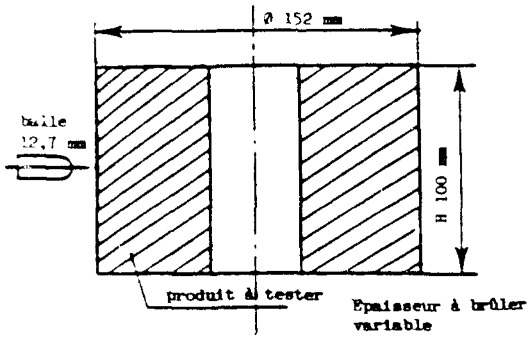
1 - ESSAIS EXPERIMENTAUX

Préliminaire : rappel de l'essai

Pour expliquer la détonation retardée inattendue, plusieurs hypothèses ont été formulées (2). Tout d'abord, il a fallu reproduire la détonation et pour cela définir une maquette représentative. Un bloc plein de ce propergol ne détone pas dans les mêmes conditions.

La maquette est en propergol nu de diamètre (ϕ = 152 mm), de hauteur (H = 100 mm) avec un canal central de diamètre variable posée sur un bâti selon une section droite. Elle est soumise à l'agression radiale d'une balle de 12,7 mm perforante modèle F1 dont la vitesse est voisine de 1050 m/s (figure 1).

Figure 1 : Description de la maquette.



Validation du scénario

Il semble que le scénario est plus complexe qu'un classique scénario de SDT ou TDD. En effet, afin de localiser l'endroit où la détonation naît au sein du bloc, et pour suivre la propagation de l'onde de détonation, des essais ont été réalisés avec des sondes à ionisation. Ceci a permis de montrer que la détonation est reproductible et a lieu aux environs de 150 μs (dans la seconde partie du bloc) après l'impact de la balle. Ce résultat ne peut pas être confondu avec les phénomènes de SDT et DDT qui ont respectivement des temps caractéristiques de quelques dizaines de μs et quelques centaines de μs.

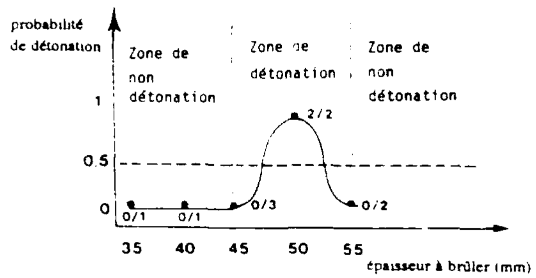
Les photos RX montrent que la balle pénètre dans la seconde partie du bloc aux alentours de 100 μs et que les fragments de propergol suivent la balle.
Pour déterminer les paramètres qui rentrent en jeu dans ce phénomène, des essais ont été réalisés en fonction de différents paramètres :

- épaisseur à brûler
- température
- structure
- vitesse de la balle et épaisseur à brûler.

L'effet de l'épaisseur à brûler (web)

Ce paramètre a une grande importance puisque une détonation a lieu à 50 mm alors qu'à 35, 40, 45 et 55 mm, nous observons seulement une combustion partielle et même fragmentation du matériau (figure 2).

Figure 2 : Courbe Probabilité de détonation en fonction du web



résultat : 0/1 = 0 détonation/un essai

En fait, il existe une zone où il y a une probabilité de détonation pour certaines épaisseurs à brûler, d'où l'importance de la géométrie du bloc sur le résultat de vulnérabilité.

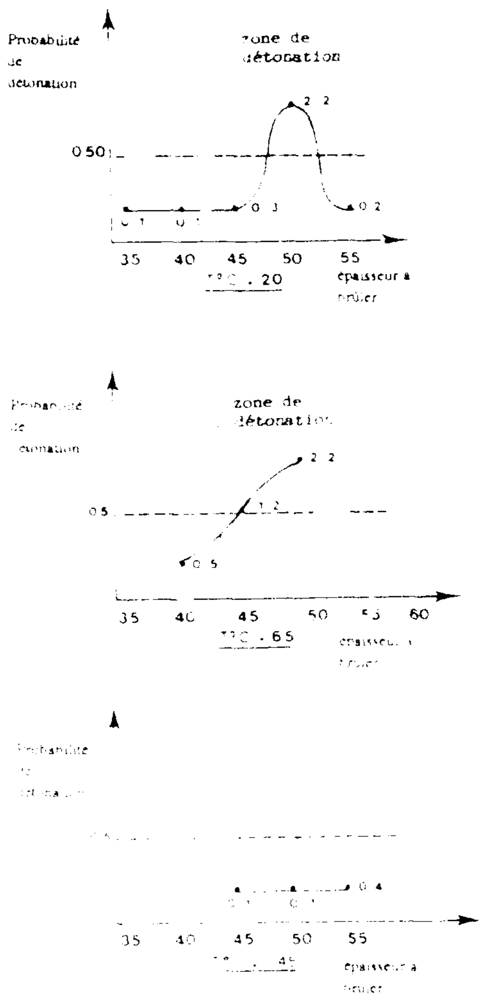
NB : Cette forme de courbe peut légèrement évoluer pour une autre fabrication du même matériau.

L'effet de la température

3 températures ont été étudiées : - 45, + 20 et + 65°C.

La figure 3 nous montre le changement de la zone de détonation en fonction de la température.

Figure 3 : Probabilité de détonation en fonction du web et de la température du bloc (bloc Φ = 152 mm, H = 100 mm)



La sensibilité à la mise en détonation à l'impact de balles croît avec la température :

- pas de détonation à - 45°C.

- seuil en épaisseur diminue quand la température augmente,

- la zone de sensibilité s'élargit.

Ce rôle de la température a déjà été mis en évidence sur les tests suivants

- en résistance à la fragmentation dangereuse, le passage de 20 à 80°C fait passer la VLI de > 288 m/s à 175 m/s, pour 18 MPa.

- à l'IAD, le nombre de cartes va de 125 cartes à 20°C à 150 cartes à 75°C.

- à l'aptitude à la détonation contre paroi plane, la vitesse seuil évolue de 480 m/s à 20°C à 450 m/s à 65°C.

- sur la vitesse de propagation des défauts.

Effet de la structure

Quelques essais avec quatre natures d'enveloppes ont été réalisées : acier, carbone, feuille d'acier roulée collée, et PMMA.

Les premiers résultats obtenus montrent que :

- l'enveloppe en acier ordinaire est pénalisante par rapport au bloc nu puisque le seuil de détonation en épaisseur à brûler est plus faible (40 mm au lieu de 50 mm).

- Les enveloppes carbone, feuille d'acier roulée et PMMA semblent améliorer le comportement des maquettes puisque pour des épaisseurs pour lesquelles il y avait détonation sur bloc nu, la détonation disparaît avec ces structures. Un programme complémentaire est en cours de réalisation pour confirmer les résultats.

Effet de l'épaisseur à brûler et de la vitesse de la balle.

Un plan d'expérience a été élaboré en faisant varier les deux paramètres : épaisseur à brûler et vitesse de balle.

Trois vitesses ont été étudiées :

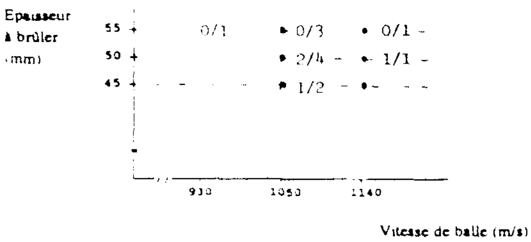
930, 1050 et 1140 m/s, ceci aux épaisseurs à brûler variant de 45 à 55 mm.

La figure 4 nous montre la réponse du propergol en fonction de ces 2 paramètres.

A 55 mm, on n'observe aucune détonation quelle que soit la vitesse de la balle dans le domaine 930 - 1140 m/s.

Les domaines du plan sont à terminer afin de pouvoir conclure sur les autres épaisseurs.

Figure 4 : probabilité de détonation du propergol en fonction de la vitesse de balle et de l'épaisseur à brûler.



Conclusions

De tous ces essais expérimentaux ressortent plusieurs paramètres importants, jouant un rôle dans le résultat à l'épreuve d'IPB :

- nature de la structure et épaisseur à brûler de propergol (architecture),

- vitesse de la balle,

- température du propergol.

2 - SIMULATION NUMERIQUE DE L'IMPACT DE BALLE

2.1. Principe de la simulation

La géométrie décrite dans ce paragraphe est celle du cas de référence et se définit comme suit :

- diamètre extérieur : $\Phi_e = 152$ mm

- diamètre du canal : $\Phi_c = 50$ mm

- hauteur : H = 100 mm.

La trajectoire de la balle suivant un diamètre avec des effets relativement localisés, a amené une modélisation en axisymétrique. Les cylindres sont ainsi modélisés par des sphères. Cette modélisation permet d'optimiser les temps de calcul tout en restant représentatif d'un point de vue phénoménologique. On gardera ainsi à l'esprit que les niveaux de pression ne sont pas à prendre en compte dans l'absolu. L'analyse est qualitative et donne un ordre de grandeur quantitatif

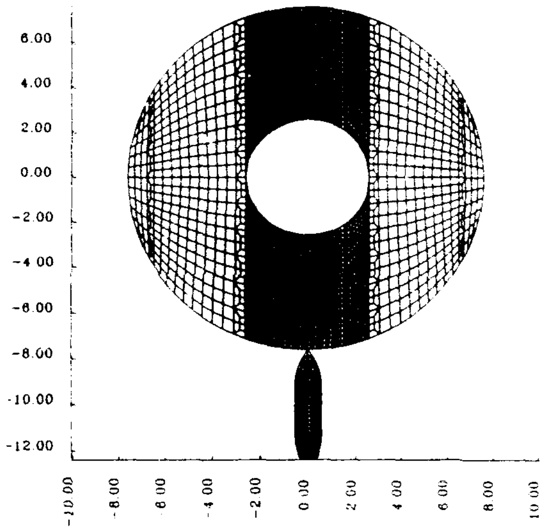
Seul le noyau de la balle est modélisé avec une vitesse de 1050 m/s. Cette vitesse correspond à une vitesse pour laquelle la maquette de référence détone quasi systématiquement à 20°C. Le code LS-DYNA 2 D (3) a été utilisé pour réaliser l'étude.

2.2. Analyse du cas de référence

La maquette a été modélisée avec 1541 éléments et 1661 noeuds en utilisant un modèle érosif (figure 5).

Figure 5

d = 152 e = 50 erosion v = 1050 m/s



Avec ce modèle, les mailles dépassant la déformation plastique d'érosion disparaissent, ce qui entraîne l'érosion du matériau le plus tendre.

La simulation a été menée jusqu'à perforation complète de la maquette. Lorsque l'on analyse l'histogramme de pression d'un élément placé proche de l'axe de symétrie à mi-épaisseur de la partie arrière point A, on constate deux pics de tension avant la compression due à la balle (figure 6).

Figure 6

d = 152 e = 50 erosion v = 1050 m/s

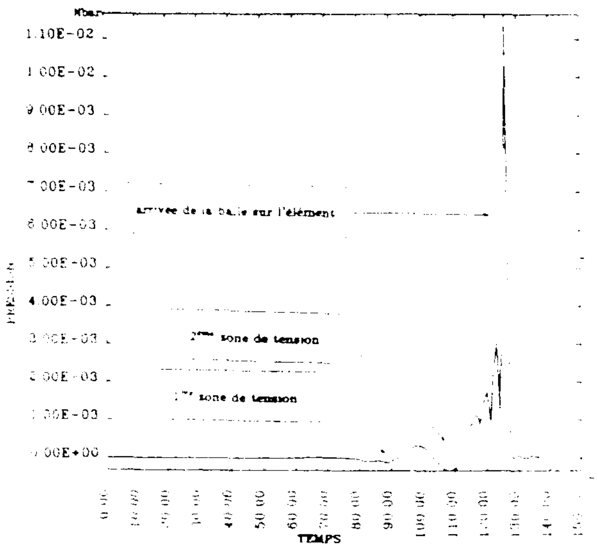
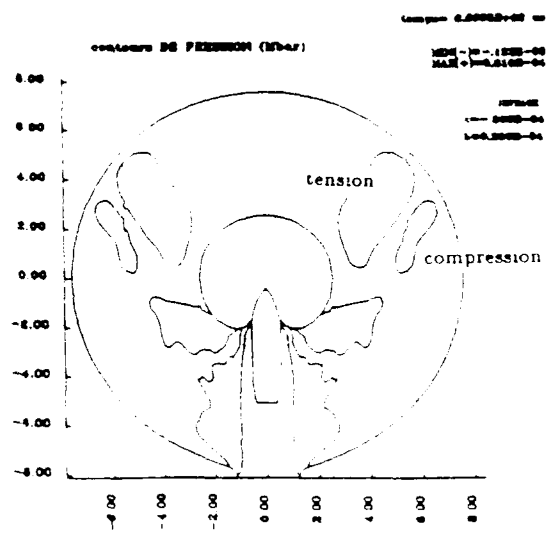


Figure 7

d = 152 e = 50 v = 1050 m/s



L'impact de la balle génère une onde de compression sphérique qui au niveau du canal se décompose en deux ondes pour le contourner. Ces ondes s'atténuent très vite en raison en particulier des détentes latérales. Elles arrivent à environ 70 μs au niveau du point A en se focalisant. Il ne reste plus que quelques dizaines de bars.

Une tension due aux détentes latérales et au trou de perforation en arrière de la balle remonte également dans le propergol. Cette tension se cumule à celle due à la réflexion de l'onde de compression précédente pour former le premier pic de tension.

Lorsque la balle atteint le canal central, la compression générée par la pointe de la balle se propage dans la maquette en contournant le canal (figure 7).

Ces deux ondes de compression atténuées en particulier par des détentes latérales se focalisent dans la partie arrière. Cette onde focalisée passe au niveau du noeud de mesure entre 90 et 100 μs. La réflexion sur la surface arrière de la maquette génère des tensions qui redescendent dans la partie arrière juste avant l'arrivée de la balle.

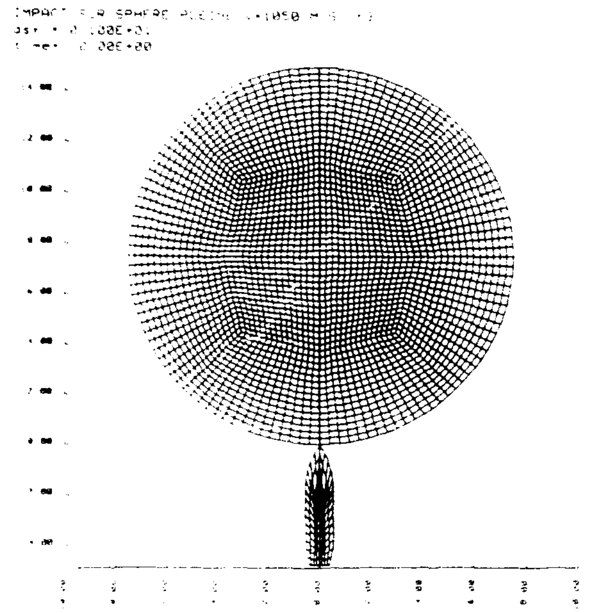
On a ainsi le deuxième pic qui apparaît sur les courbes (figure 6). Ce deuxième pic de tension (330 bar) plus élevé que le premier, atteint un niveau tel que l'on peut supposer le propergol endommagé.

La détonation obtenue sur ce type de maquette peut s'expliquer par l'endommagement préalable à l'impact de la balle de la partie arrière du système. Le matériau ainsi endommagé est plus sensible pyrotechniquement au choc.

2.3 - Comparaison avec un cylindre sans canal

La maquette pleine a été discrétisée par 2267 éléments et 2458 noeuds (figure 8).

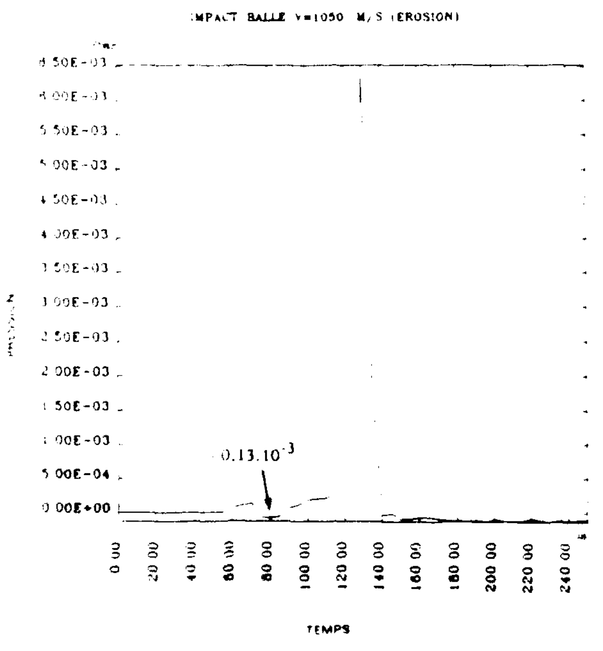
Figure 8



Le dépouillement des calculs a été effectué en se plaçant au même niveau sur l'axe de symétrie que précédemment.

On constate l'absence de deuxième pic de tension (figure 9).

Figure 9



Le schéma de propagation des ondes est un peu différent en raison de l'absence de canal central. L'onde de compression qui se propage à environ 2200 m/s dans le propergol se réfléchit sur la surface libre arrière donnant des tensions. Ces dernières sont faibles, l'atténuation de l'onde de compression étant importante. La compression entretenue par la perforation de la balle empêche d'ailleurs cette zone de tension de se développer. L'amplitude de cette compression est, dans les mêmes conditions de calculs deux fois plus faible que dans le cas précédent. Il est raisonnable de considérer que la balle perfore un matériau qui reste "homogène" mécaniquement pendant toute l'agression (ceci en amont de la balle).

2.4 - Corrélation vitesse de la balle - épaisseur à brûler

Le présent paragraphe cherche à montrer l'importance de la synchronisation entre la vitesse de la balle et le trajet parcouru par les ondes de pression.
D'autre part, la vitesse de balle induit les niveaux de tension enregistrés. Les géométries ainsi étudiées sont :

- diamètre extérieur ϕ_e = 152 mm,
- diamètre du canal :
  . $\phi 1_c$ = 70 mm (ép. 40 mm)
  . $\phi 2_c$ = 30 mm (ép. 60 mm)
- hauteur maquette H = 100 mm.

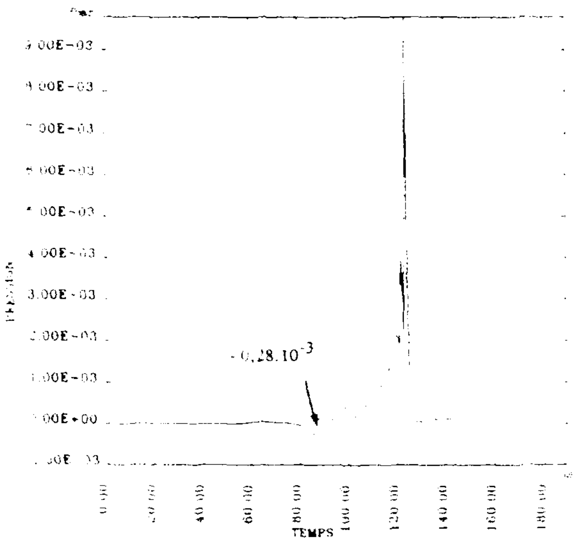
—> Maquettes d'épaisseur de propergol 60 mm.

Deux vitesses différentes ont été envisagées pour la balle : v = 950 m/s, v = 1050 m/s.

A la vitesse standard de l'essai, c'est à dire à 1050 m/s, on constate figure 10 que la tension qui se développe à l'arrière de la maquette est faible. Elle n'atteint que 286 bar (t = 88 μs) ce qui est trop faible pour endommager de façon notable le propergol.

Figure 10

d = 152 e = 50 erosion v = 1050 m/s

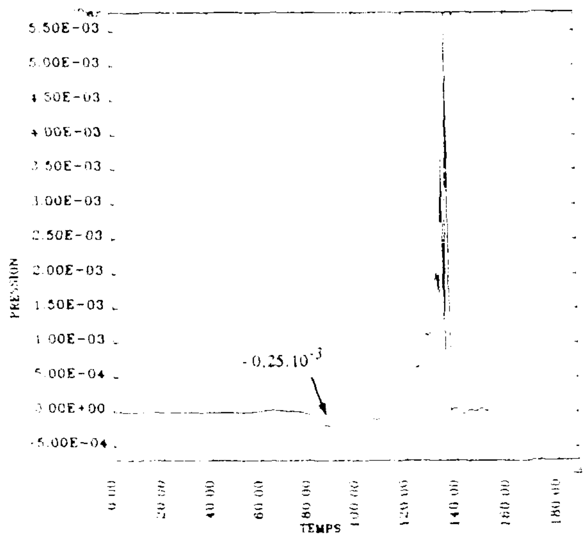


Cette première tension, due à la réflexion des ondes de compressions issues de l'impact de balle en face avant, n'est jamais suffisante pour générer assez d'endommagement. Il était donc intéressant d'envisager une vitesse de balle plus faible pour laisser les ondes se combiner de façon à avoir le deuxième pic de tension mis en évidence lors d'une étude précédente . La compression due à la perforation de la partie arrière de la maquette par la balle ne génère pas de réaction pyrotechnique, l'endommagement n'étant pas suffisant.

Pour une vitesse initiale d'impact de 950 m/s, on constate figure 11 que les niveaux de tension dans la partie arrière de la maquette restent faibles. Le deuxième pic de tension reste faible car la balle arrive encore trop vite. Par contre, si l'on envisage une vitesse de balle plus faible les niveaux de sollicitations sont insuffisants pour obtenir une réaction pyrotechnique.

Figure 11

d = 152 e = 60 erosion v = 1050 m/s



Le fait que la vitesse de la balle soit plus faible permet donc de voir l'allée et le retour des ondes dans la partie arrière de la maquette. L'endommagement restera faible et ne rendra pas le matériau plus sensible à l'impact de la balle.

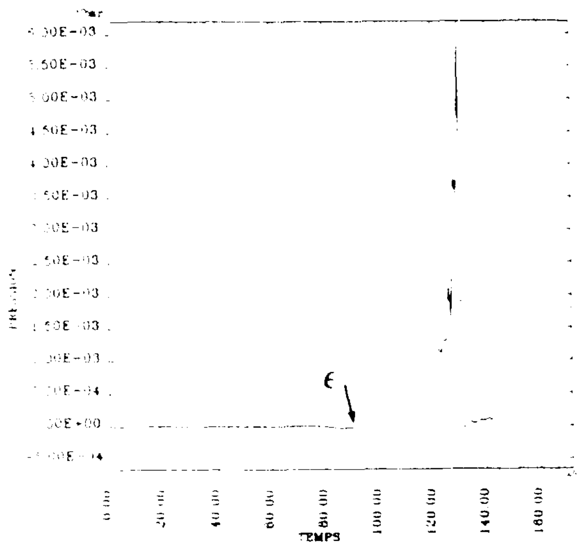
A la vitesse d'impact standard, le signal de pression tracé en fonction du temps dans la partie arrière de la maquette présente la même allure que dans le cas de la maquette pleine. Le canal n'est donc pas assez important. Expérimentalement aucune réaction pyrotechnique n'a été enregistrée avec une telle maquette.

---> Maquettes d'épaisseur de propergol 40 mm

Deux vitesses d'impact ont été envisagées pour l'étude de ce type de maquettes : v1 = 1050 m/s et v2 = 1250 m/s.
A la vitesse de 1050 m/s on retrouve bien le 2ème pic de tension mis en évidence lors de l'étude de comparaison entre la maquette pleine et la maquette d'épaisseur 50 mm. Cette tension plus faible semble insuffisante pour générer un endommagement suffisant du propergol. Le signal de pression à mi-épaisseur de la partie arrière point A de la maquette est fourni figure 12.

Figure 12

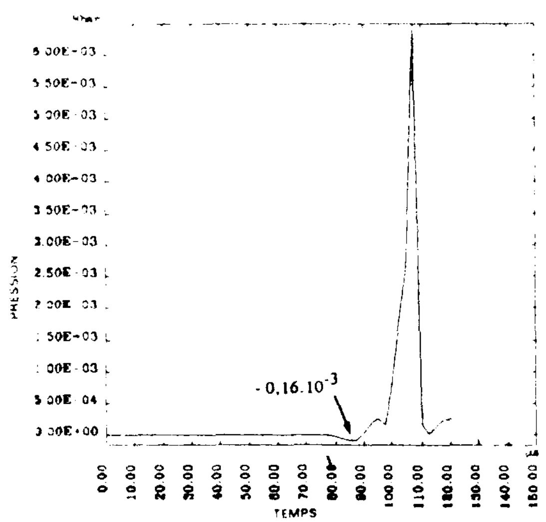
d = 152 e = 40 v = 1050 m/s



Pour la vitesse de 1250 m/s, la balle arrive avant que les ondes se soient combinées de façon à générer de la tension dans la partie arrière de la maquette (figure 13).

Figure 13

d = 150 e = 40 erosion v = 1250 m/s



On peut donc dire que si la balle a une vitesse trop grande elle précèdera la formation du second pic de tension empêchant l'endommagement du propergol et par là même sa sensibilisation au choc.

Inversement si la vitesse de la balle est trop faible, on aura formation du deuxième pic de tension mais d'un niveau trop faible pour endommager le propergol. En corrélation avec cela l'onde de compression due au second impact sera plus faible.

3 - CONCLUSIONS

Ces travaux ont montré que la mise en détonation des moteurs à propergol solide lors d'un impact de balle, pouvait s'expliquer par d'autres scénarii que les traditionnels DDT et SDT. Notamment pour les chargements à canal, le mécanisme de XDT pouvait être exacerbé pour des épaisseurs ou vitesses de balle très particulières. Ce résultat confirme une nouvelle fois que la vulnérabilité n'est pas qu'un problème de sensibilité du propergol. En fait, l'immunité d'une munition dépend de son architecture et doit être prise en considération comme une performance lors de son dimensionnement.

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Discussion

QUESTION BY VICTOR, US: Have you varied the diameter of the charges tested in these bullet impact tests?

ANSWER: Yes, it is a parameter we vary. However, at the experimental level, we have to limit ourselves as to the size we can test. Indeed, for the charge diameters of about 200 mm, in the barrel the bullet could deviate so that the thickness of the propellant in the second part is not precisely known, and is therefore a parameter for further testing. Nevertheless, we are actually doing tests of 170 mm caliber.

QUESTION BY VAN DER STEEN, THE NETHERLANDS: How did you model the increase in sensitivity of the damaged propellant in your simulations?

ANSWER: On the one hand, Tom Boggs and his colleagues at NWC have shown that a freshly damaged propellant has a sensitivity which may be multiplied by a factor of 10. On the other hand, through our own modelling, we have shown that the XDT phenomenon, for example in the gap test, can be explained by a more important sensitivity parameter of the damaged propellant caused by the passage of the first compression wave through the propellant and the resultant internal stress which follows.

QUESTION BY MENKE, FRG: Does the shock modelling take care of different mechanical properties in a propellant with viscoelastic mechanical properties?

ANSWER: Yes, the modelling does take into account the mechanical properties of the propellant.

EFFECT OF CASE THICKNESS AND PROJECTILE GEOMETRY ON THE SHOCK INITIATION THRESHOLD FOR A GIVEN EXPLOSIVE

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Summary

An unacceptable response from a munition can be obtained by a variety of mechanisms associated with the impact of a projectile. A prompt response, leading in many cases to full detonation, is usually linked to the stimulus provided by the impact shock. Although shock initiation forms only a part of the threat posed by projectile impact, its importance merits the present study into the effectiveness of protective barriers, and some of the limits associated with the phenomenon. This paper examines the protection given by barrier thickness and material against a range of projectile geometries for impacts involving a given explosive. The type of geometry which can cause shock initiation is discussed and the nature of the shock examined. Differences between 1D and divergent shock initiation are explored.

1. INTRODUCTION

In attempting to protect munitions from projectile attack it is important to understand the hazards posed by various geometries (and orientations) of projectile, and the protection given by different barrier thicknesses and materials. In this context one of the major hazards to a munition originates from the production of the impact shock and its transmission into the explosive.

In the past extensive effort has been devoted to developing criteria aimed at predicting the explosive's response to the simplest of such shocks, ie the 1D shock such as that produced by flying plate impact. However, the majority of impacts that are likely to occur to a munition (such as those from bullets and fragments) do not produce such a shock, either because of the projectile geometry or the thickness and composition of the barrier. The most likely form of shock to be transmitted into the explosive is one in which the flow is diverging, producing a shock that instantly starts to decay with time and, for the majority of velocities in the bullet/fragment regime, has a decreasing pressure profile linking the shock to the barrier or projectile.

A systematic experimental study is reported in this paper of the effect of both projectile geometry and barrier conditions on initiation threshold. This study illustrates the differences beween 1D and divergent shocks in producing detonation. Theoretical work links such differences to the effect of the degree of shock divergence, and formulates a criterion which predicts the initiation theshold for divergent shocks.

2. EXPERIMENTAL ASSEMBLY

The majority of results reported in this paper were obtained from impacts into a charge that was 100mm long by 57mm diameter. The charge was contained in a 9mm thick steel cylindrical casing, open at one end. The open end of the charge (which was subject to impact) was either bare or covered by a barrier of steel or aluminium. The explosive used was PE4, a mouldable plastic explosive containing 88% RDX and 12% grease as an inert binder. Material details are listed in Table 1.

Table 1. Hugoniot data assuming a linear shock/particle velocity relationship (w=A+Bu)

Material	Density (Mg/m^3)*	A (km/s)	B	Ref
Mild Steel	-	3.596	1.6863	1
Aluminium	2.68	5.27	1.37	2
PE4(solid phase)	1.60	2.5+	2.0+	-

* Densities for PE4 experiments were 7.81 Mg/m^3 for the projectiles and 7.78 Mg/m^3 for the barrier.

+ Estimated values for A and B. In the above w is the shock and u the particle velocity.

A steel projectile 25.4mm long by

13.15mm diameter was used. Three types of tip geometry were investigated; flat ended; conical tips, and rounded ends. The internal angle of the conical tips was varied from 165° to 30°. The round nosed projectiles had radii of curvature of 6,6mm and 8.2mm. In all instances the tip geometry was attached to the 13.15mm diameter rod. The projectiles were housed in a nylon sabot and fired from a 30mm RARDEN gun.

The event was back-lit by flash bulbs and filmed using a 1/4 height fastax camera operating at about 30,000 fps. The film record was used to measure the projectile velocity and to check for yaw. In those experiments in which initiation delays were measured, a make-foil was placed on the front of the charge and ionisation probes placed in contact with the explosive at a number of positions on its surface.

3. EXPERIMENTAL RESULTS

3.1 Effects of Projectile Geometry and Barrier Thickness

Figure 1 shows the threshold velocities required for detonation when the charge was covered by aluminium barriers of various thicknesses. The results for flat-ended (180°) and four conical-tipped projectiles are shown. The error bars indicate the spread between the lowest velocity to produce detonation, and the highest to produce a non-detonation. Experiments were also conducted using 90° and 30° cones, but no detonations were recorded up to the maximum velocity of the gun (about 2000 m/s). Figure 2 compares results for the round-ended rods with those from flat-nosed impacts, again using aluminium barriers of various thicknesses.

Examination of figure 1 shows a marked difference between the initiation threshold for the flat-ended rod and those of the conical-tipped projectiles. In the latter type of projectile, cone angles between 120° and 165° produce threshold data which are remarkably similar. The threshold velocity rises almost linearly with increasing barrier thickness for a given cone angle, and the change in angle produces an almost constant shift (allowing for experimental uncertainty) in the threshold velocity. This is in contrast to the flat-ended projectile which shows quite a complex curve, although for the thicker barriers this curve starts to approach the behaviour exhibited by the cones. The emergence of a similar pattern is shown in figure 2 for the round-nosed rods, although the restricted amount of data does not permit such generalised statements.

This complexity of the flat-nosed projectile's threshold curve raises the possibility of changes in initiation mechanism with increasing barrier thickness. For large changes in mechanism, eg between shock to detonation transition (SDT) and deflagration to detonation transition (DDT), it was expected that significant differences in the time of explosive response would be observed. Film records, which have an interframe time of about 30μs, showed no observable difference for responses from thin and thick metal barriers. To obtain a more accurate assessment of delay time, a number of experiments were performed in which ionisation probes were placed at various positions on the surface of the explosive. These probes gave arrival times of the detonation wave for impacts designed to be just above the initiation threshold. The results show that for all thicknesses of aluminium barrier tested (3mm, 9mm and 10mm) there is less than a 5μs delay for the onset of detonation once account has been taken of the times for the shock to traverse the barrier, and for the detonation front to reach the probes. Consequently there is unlikely to be a large scale change of mechanism for these impacts, although changes within the SDT mechanism will be shown later in this paper to almost certainly take place.

The efficiency of the three types of projectile geometry at initiating covered explosives is shown in figure 3. Here the average of each detontion/non-detonation point is taken. This velocity is normalized by the corresponding bare threshold velocity for the particular type of projectile. It can be seen that flat-nosed rods are the most efficient at initiating the explosive, although at very thick barriers (above about 7mm of aluminium) the slope of the normalized velocity curve is approximately parallel to that of the cones. Conical projectiles follow very similar paths for cone angles of 120° and above. Less efficient than this class of cone (although based on somewhat limited data) is the round-nosed tip.

3.2 Effect of Barrier Material

Figure 4 shows the difference in the initiation thresholds for PE4 covered by steel and aluminium. The apparent increase in sensitivity of the explosive covered by thin aluminium is postulated as being the result of the barrier's Hugoniot lying between those of the projectile and explosive. A more exhaustive discussion of this subject is given in ref.3. The main point to note is that about 5mm of aluminium is required to return to a threshold velocity equal to an impact into the bare explosive.

A limited number of experiments were carried out using a 10mm thick rubber barrier. Three experiments were performed at about the same velocity (2000 m/s with the flat-ended rod), but with different degrees of confine-

ment. A plastic case, and a plastic case with steel backplate did not produce detonation, while the charge detonated in a steel case but with a delay of the order of 10-100 μs. The combination of relatively long delay (compared to a similar thickness of aluminium) and the need for confinement (the response with the aluminium barrier was the same regardless of case material) indicates a more fundamental change in mechanism than that observed for barrier thickness. It seems clear that the rubber does not transmit a shock of sufficient amplitude and duration to cause initiation at this impact velocity. However the exact initiation mechanism under these conditions is not known at present.

4. THEORETICAL INTERPRETATION

4.1 Effect of Projectile Geometry on Initial Shock Structure

Unless the velocity of the projectile as it penetrates the explosive is supersonic (discussions about such conditions, which mainly apply to shaped charge jet impacts, are given in ref.4), the initial impact shock quickly separates from the projectile and, unless reaction is triggered, decays as rarefactions from the periphery move into the shocked material. The quantity of explosive shocked to a given level, and the subsequent history of that material, depends critically upon the initial shock formation, which in turn depends upon the geometry of the projectile. Figure 5 shows a 2D Eulerian hydrocode simulation of the shock structures generated for the three types of projectile impacting bare explosive at the same velocity.

A flat-nosed rod produces a significant volume of 1D shock which, for relatively thin barriers, can be transmitted into the explosive. Theoretical considerations (ref.3) show that some 10mm of aluminium is required to prevent any transmission of 1D shock from the 13.15mm diameter steel projectile. However, only very small volumes of 1D shock are generated in the explosive for aluminium barriers thicker than about 7mm. Figure 3 shows that the 1D shock regime is associated with the lowest impact velocity needed to cause initiation. For thicker barriers a diverging shock is passed into the explosive, similar in character to those generated by conical projectiles, although different in amplitude (a fuller discussion on the differences between these projectiles is given in the next section).

Impacts by conical projectiles will not produce a 1D shock volume, although high pressures are produced in the divergent shock providing the cone angle and velocity are such as to give a supersonic impact along the conical surface. Figure 5 shows that for such an impact the shock structure consists of a transient, small volume of shock which is at very high pressure. This shock is associated with an annulus which is the initial region of contact between the conical surface and the target, and as such moves with this contact region. The main shock volume behind this contact ring is at a much lower pressure with a flow velocity away from the axis of symmetry. The divergent nature of this shock means that parameters such as pressure and internal energy in this volume are below those obtained for an equivalent impact velocity producing a 1D shock. Where the contact ring is formed in the explosive, it is postulated that the transient and highly localized nature of the contact shock makes it unsuitable to be the initiation mechanism. No sooner has material been raised to this elevated pressure than it expands and cools to conditions in the larger volume. The theory advanced in the next section assumes that it is the larger and less volatile divergent shock volume that provides initiation. This is certainly true for most covered explosives where only the divergent shock is transmitted across the barrier.

The dividing line between supersonic and subsonic cone impacts is obtained by noting that the outward radial velocity of the contact ring along the target surface is given by $v/\tan(90-\Phi/2)$, where v is the impact velocity and Φ is the cone angle in degrees. By equating this to the ambient sound speed in the target material (approximated by A for materials in Table 1), the critical impact velocity is obtained. Supersonic impacts are generated in bare PE4 for angles above 140° at 900 m/s, and above 100° at 2000 m/s. In these impacts release waves cannot cross the contact ring until the conical surface is fully in contact with the target. In contrast subsonic impacts immediately allow rarefactions across the contact ring to erode the already divergent shock. Hence the difficulty of causing initiation, even for bare impacts, with 90° and 30° cones, both of which are subsonic at 2000m/s.

Round-nosed projectiles produce a similar shock structure to that described for the cone in qualitative terms, but have quantitative differences. Conditions at the contact ring start by being supersonic near the initial point of contact, and become subsonic as the angle between the target and a tangent to the curved projectile surface increases. Indeed the radial velocity of the contact ring initially tends to infinity, inducing a 1D, or near 1D, shock in a small volume of target material. The projectile curvature then produces an increasingly divergent shock, and eventually allows rarefactions to cross the contact ring before the

projectile surface is in complete contact with the target. For comparison with other projectiles, the shock structure evolves from an approximation to a flat-nosed rod, through a supersonic cone and finishes as a subsonic cone.

The overall degree of shock divergence for a round-nosed impact, and its role in initiation, is difficult to estimate. Ref.5. postulates that the near 1D portion of the shock is responsible for triggering initiation in bare charges. However, this would not usually be transmitted across a barrier, and the divergent shock that is transmitted will have undergone greater erosion, due to the subsonic portion of the shock structure, than a supersonic cone of the same diameter. Hence the trend shown in figure 3 of the round-nosed projectile being less efficient in initiating covered explosives than a supersonic cone.

Differences in the bare (and unconfined) explosive response to flat and round-nosed projectiles are given in ref.5. Under these circumstances the response, as measured by blasst output, becomes more complex as the projectile is changed from flat to round-nosed. A flat-nosed geometry produces either a blast which is equivalent to detonation, or has no blast output. The round-nosed projectile can produce an additional response which lies between these extremes. Such a response was ascribed to reaction being triggered in the early stages of the shock evolution, but not being supported by the subsequent divergent nature of the flow which would tend to expand and cool the material. Some tendency towards a similar trend for 120° cones (ref.6) has been noted, in which reactions, which fall short of full detonation, have been measured. The situation in covered and confined explosives is not so easily determined since non-shock mechanisms can give sub-detonative responses for any of the projectile types.

It appears from the above that a qualitative estimate of projectile efficiency and explosive response characteristics can be made on the basis of the shock structure transmitted into the explosive. The production of a 1D shock is the most efficient method of initiation in the projectiles investigated (it is possible that a focused shock would give greater efficiency, but experimental data appears to be lacking). Divergent shocks are less efficient and give less support (at least in bare explosives) to the reaction growth phase.

4.2 Initiation Criterion for Divergent Shocks

Previous work has modified a critical energy criterion, developed by Walker and Wasley (ref.7) for plate impacts, to apply to flat-nosed rods (ref.8). This criterion is based on the transmission of a 1D shock into the explosive, and has recently been adapted to apply to impacts into covered explosives (ref.3). Figure 6 shows the 1D theory to provide a good fit to the initial region of the threshold curve for flat-ended impacts into an aluminium barrier. However, this theory, in its present form breaks down for impact above about 7mm barrier thickness, despite experimental data showing a prompt (ie shock) detonation.

Figure 7 shows a simulation of the thick-barrier experiments using a 2D Eulerian hydrocode. This predicts the existence in the explosive of a divergent, but still high, shock regime. However, the radial change in shock parameters is small compared to the change occurring in the longitudinal direction between the shock front and the barrier. In proceeding radially outwards along the shock front from the axis of symmetry, parameters, such as pressure, change relatively slowly over a distance of the order of the original projectile radius. The insertion of a barrier means that the shock, once it enters the explosive, is usually at some distance from the original impact, ie it is effectively a "far field" phenomenon in which the shock curvature has been considerably reduced. The original shock divergence produced near the impact site appears to be translated into differences in the longitudinal rarefaction (see below). The detailed mechanisms in this translation have still to be identified.

To a first approximation, such a wave would correspond to a plane shock with a longitudinal rarefaction attached directly to the shock front, ie the divergence is ignored. By assuming that conditions corresponding to the average pressure on the centre-line at a given time are equivalent to those in a 1D shock of that amplitude, use can be made of existing criteria. In a plate impact the critical energy can be shown (ref.8) to have the form.

$$E_c = \rho_o d\, wu^2 /(w-u) = Pud/(w-u) \qquad (1)$$

where E_c is the critical energy (derived from flat-ended rod impacts into bare explosive), ρ_o the initial explosive density, P the shock pressure, w and u the shock and particle velocities and d the shock width. This last term is the distance between the shock front and barrier in the wave described above. For a linear relationship between shock and particle velocity,

$$w = A + Bu, \text{ and}$$

$$u = [(A^2 + 4BP/\rho_o)^{0.5} - A]/(2B) \qquad (2)$$

Using the parameters in Table 1 for PE4, and $E_c = 1.83\ MJ/m^2$, equations

(1) and (2) define the threshold shock pressure for a given shock width. Using the 2D hydrocode to model the shock evolution in the explosive, and examining the average pressure at about 0.2μs intervals, shows whether a particular impact crosses this shock threshold. The results for flat-ended rod impacts into thick barriers, and 165° cones into all barriers are compared with experiment in figure 6. Figure 8 shows the theoretical threshold for PE4, and the time dependent relationship between P and d found for, what is judged to be, threshold impacts for the two types of projectile.

It should be noted from figure 8 that the shock structure for the two projectiles is quite different. The flat-ended rod has a high average pressure which quickly decays, in contrast to the cone which has a low amplitude shock of relatively long duration. Consequently the parallel nature of the cone and the latter portion of the flat-nosed response curves in figure 3 appears to be due to similarities in the *changes* in shock structures with changing impact velocity. The off set between the two curves is probably due to the differences in shock amplitude.

The inaccuracies due to approximations embodied in the above method can be listed as follows:-

1. Inaccuracies in the hydrocode simulation.

2. Inaccuracies in the assumption that conditions at average P match those in a 1D shock of the same amplitude.

3. Inaccuracies introduced by assuming a plane shock in the radial direction.

In the first of these, the method requires large amounts of computer time and the simulation output has to be interrogated at short time intervals. Results in this paper were obtained from the commercially available 2D Eulerian code AUTODYN (version 2.37), run on a desk top machine for speed of turn round and flexibility of interrogation. However, the code in its present form is only first order accurate and so needs to be used with care. A mesh of 0.375 x 0.56mm was used in the region of interest, and wave shapes investigated at 5 cycle intervals. The pressure is located at the cell centre and, due to artificial viscosity, the main portion of the shock front is smeared over about three cells. Hence the location of the shock front is taken as the mid point of the first cell past the location of the maximum pressure. Then d is the distance between this point and the barrier. The average pressure is given by

$$P = \{P_1 + (h/h') \sum_{i=2}^{n} P_i\}/\{(n-1)\, h/h' + 1\} \quad (3)$$

where cell 1 contains the barrier/explosive interface, and h' is the distance between barrier and the edge of cell 1. The maximum pressure is located at cell n, and h is the cell width along the centre-line.

Comparison of the AUTODYN code simulations of a 1D shock with results from an analytic solution, using the materials of Table 1 and velocities in the region of interest, indicates errors in P of the order of +10%, and in d of -5%.

In the second of the above assumptions, errors are introduced because some of the explosive behind the shock front has been partially released. The material has come down an adiabat from the shock position on the Hugoniot and so the internal energy is higher, and ρ and u differ from those associated with a 1D shock pressure of the same amplitude as the average pressure in the wave. The critical energy in its most basic form is

$$E_C/d = \rho\,[u^2/2 + \epsilon] \quad (4)$$

where ϵ is the specific internal energy, and ρ the shocked density of the explosive. For a 1D shock (4) reduces to the combination of (1) and (2) already mentioned. However, if the average values (subscript A) throughout the wave are used, then (4) becomes

$$E_C/d = \rho_A[u_A^2/2 + \epsilon_A] \quad (5)$$

Since E_C/d can be equated to a 1D shock pressure, then this pressure can in turn be equated to the average values in (5). As these values can be supplied by the hydrocode, the effects of deviations from the Hugoniot should be included. Hence a better estimate of the 1D pressure corresponding to average values in the wave can be made by solving

$$0 = \rho_A \left\{\frac{u_A^2}{2} + \epsilon_A\right\} - \frac{P'[A^2+4BP'/\rho_o)^{0.5} - A]}{2AB+(B-1)[(A^2+4BP'/\rho_o)^{0.5}-A]} \quad (6)$$

where P' is the improved estimate of 1D pressure.

By obtaining the average values for ρ, u and ϵ for a number of impacts in the

region of interest, the effective error in P is found to be of the order of -10% to -15%.

For the third assumption, the average values of P and d were obtained over the shock field out to approximately the original radius of the projectile. This was only carried out on a limited sample. However, the error in this sample in P (introduced by only calculating P on the centre-line) was +8%, and the error in d was +2%.

It can be seen that the approximations made in calculating P and d have introduced errors that tend to cancel, at least in the current investigation. This work confirms that the degree of divergence in all of the impacts investigated is reasonably low. Consequently what is basically a 1D theory can still be applied with great success. However, a major portion of the energy required for initiation is now contained within the release wave attached to the shock front, rather than confined to shocked material which has yet to be released. Hence the calculation of such conditions has increased in complexity.

5. CONCLUSIONS

Of the projectiles investigated, those that passed a 1D shock into the explosive were most efficient at causing initiation. Divergent shocks, such as those produced by flat-ended projectiles through thick plates, or by conical projectiles, were less efficient. A greater loss of efficiency was found in round-nosed projectiles where part of the striking surface impacted the target at subsonic velocities. The least efficient type of projectiles was the class of cone where the entire striking surface impacted at subsonic velocity. No detonations were recorded for any impact under those conditions.

Thicker barriers obviously offer more protection against shock initiation. However, within the constraints of a munition, a realistic thickness is unlikely to eliminate the problem. In the current experiments detonation has been observed at about 2000 m/s impact velocity for both a 9mm steel barrier and a 12mm aluminium barrier.

Better protection to shock is given by the insertion of a layer of material such as rubber. However, with some barrier materials, in which the Hugoniot lies between those of the projectile and explosive, there is the possibility of a reduction in protection against shock.

The differing types of divergent shock structure, formed on impact by the different projectile geometries, appear in the explosive mainly as variations in the behaviour of the release wave connecting the shock to the barrier. The amount of divergence in the shock at these relatively large distances from the projectile is small. This allows a form of the 1D criterion to successfully predict the explosive's response to such shocks.

6. REFERENCES

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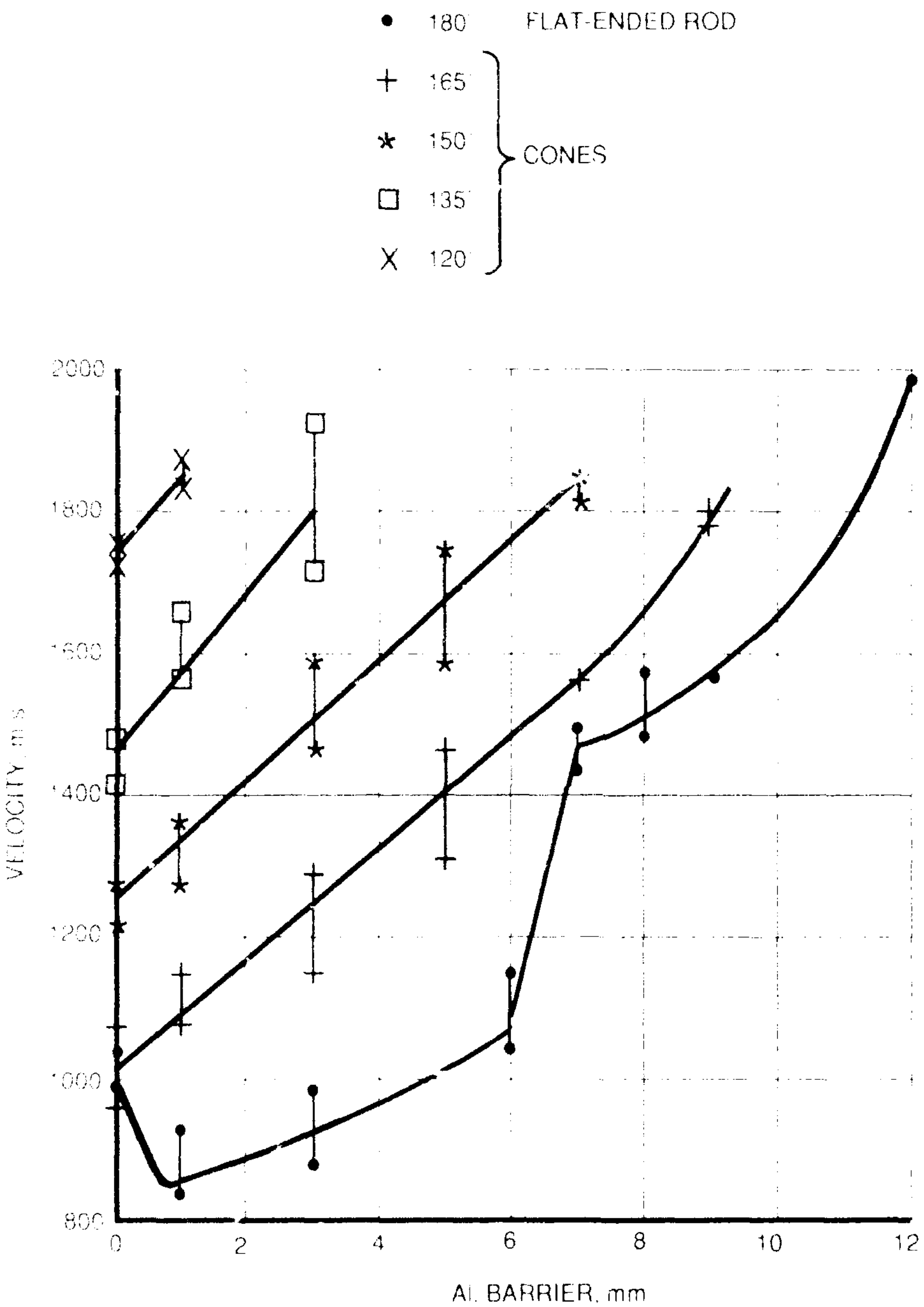

FIGURE 1. COMPARISON OF THRESHOLD VELOCITIES BETWEEN FLAT-ENDED AND CONICAL TIPPED PROJECTILES

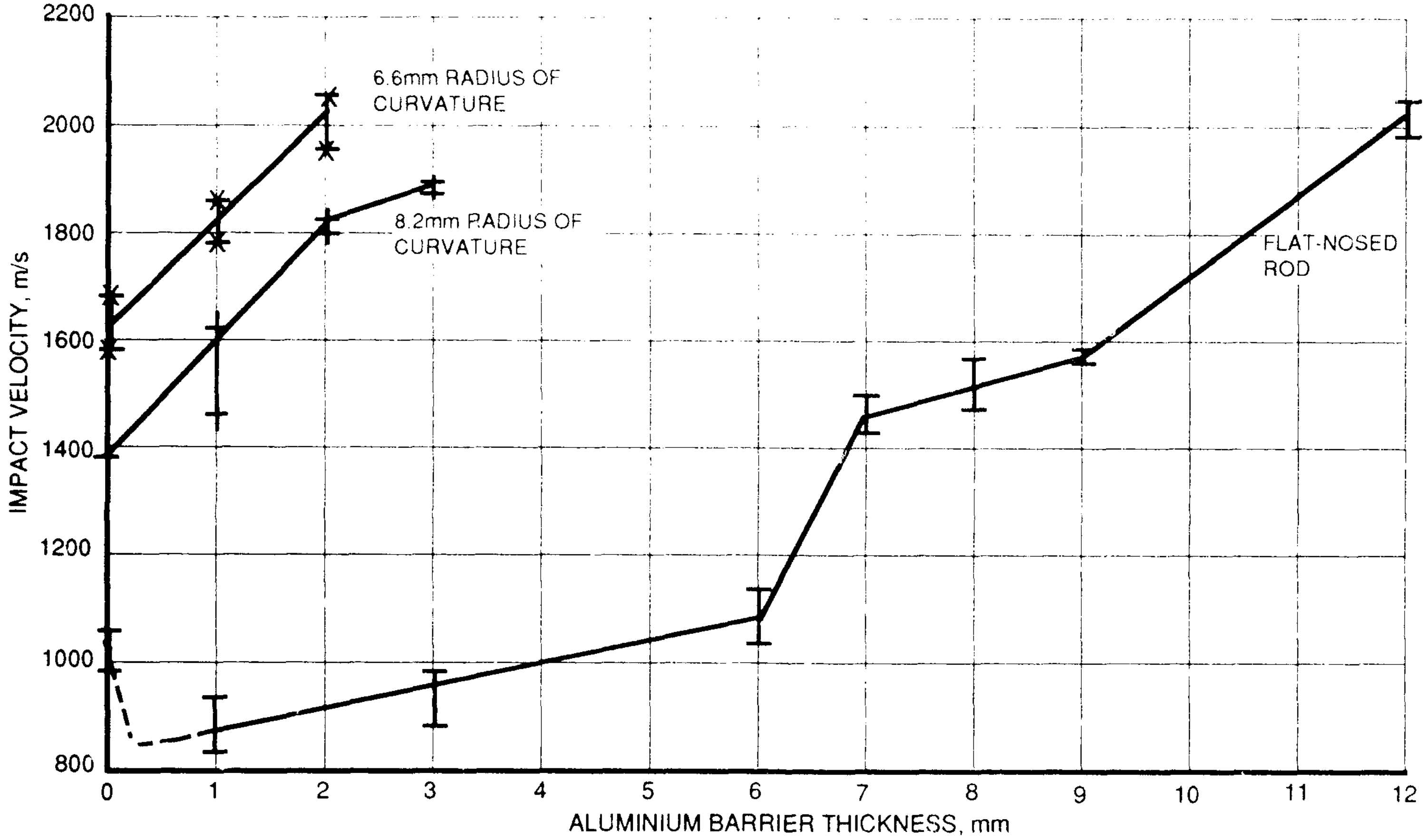

FIGURE 2. COMPARISON OF THRESHOLD VELOCITIES BETWEEN FLAT-ENDED AND ROUND-NOSED PROJECTILES

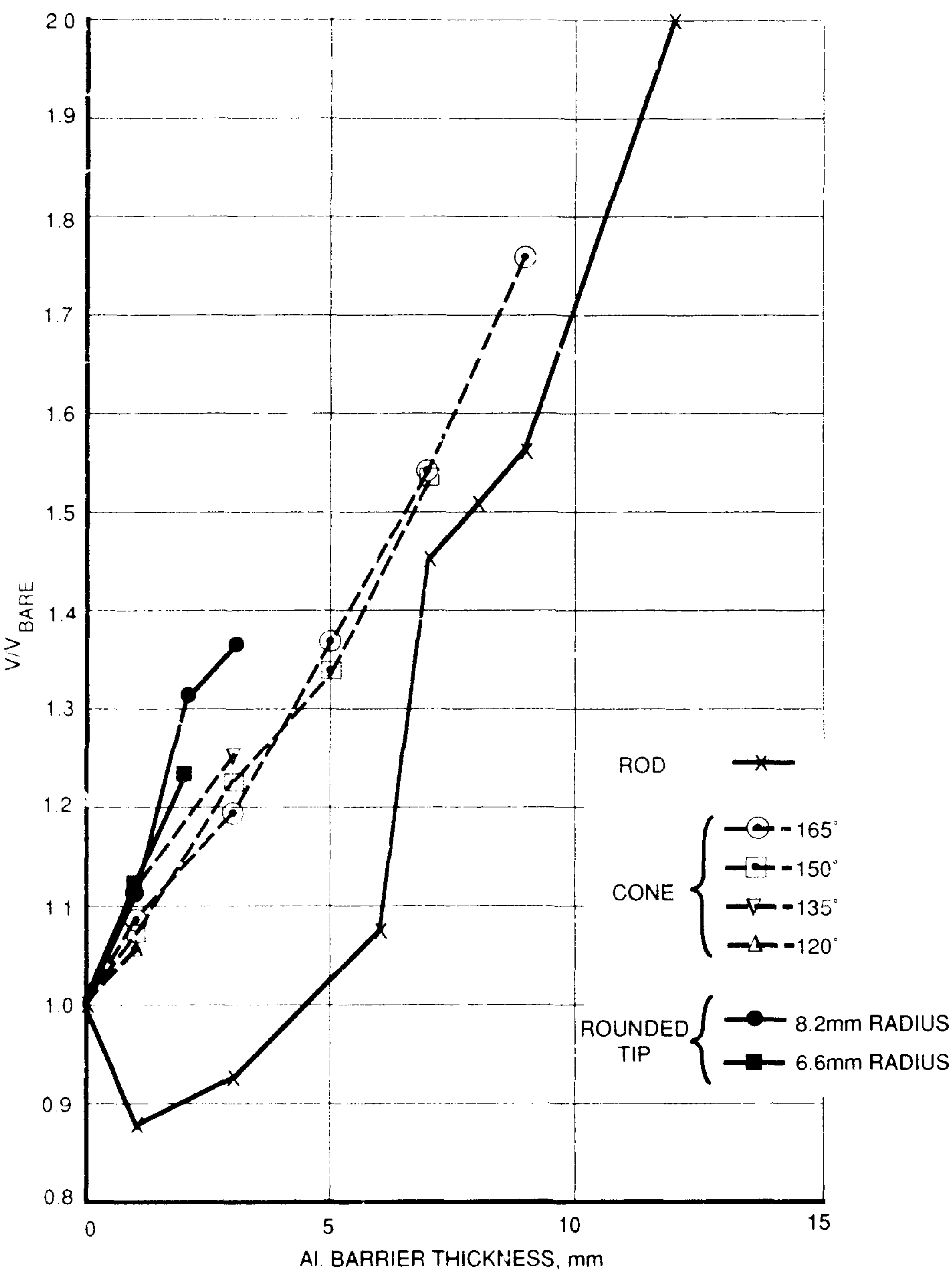

FIGURE 3. EFFICIENCY OF VARIOUS PROJECTILE GEOMETRIES IMPACTING PE4 WITH ALUMINIUM BARRIER

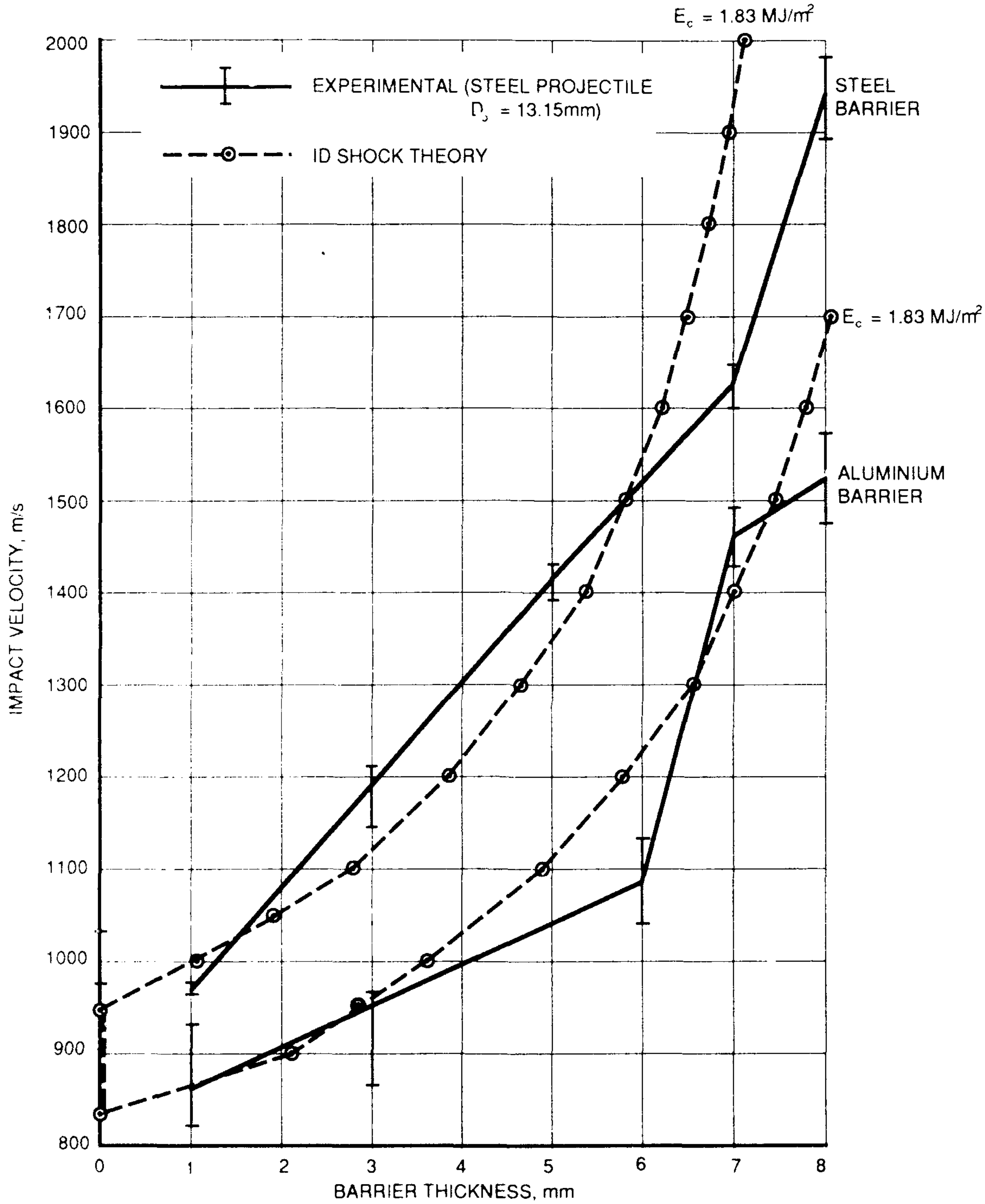

FIGURE 4. INITIATION THRESHOLDS FOR PE4 COVERED BY STEEL AND ALUMINIUM

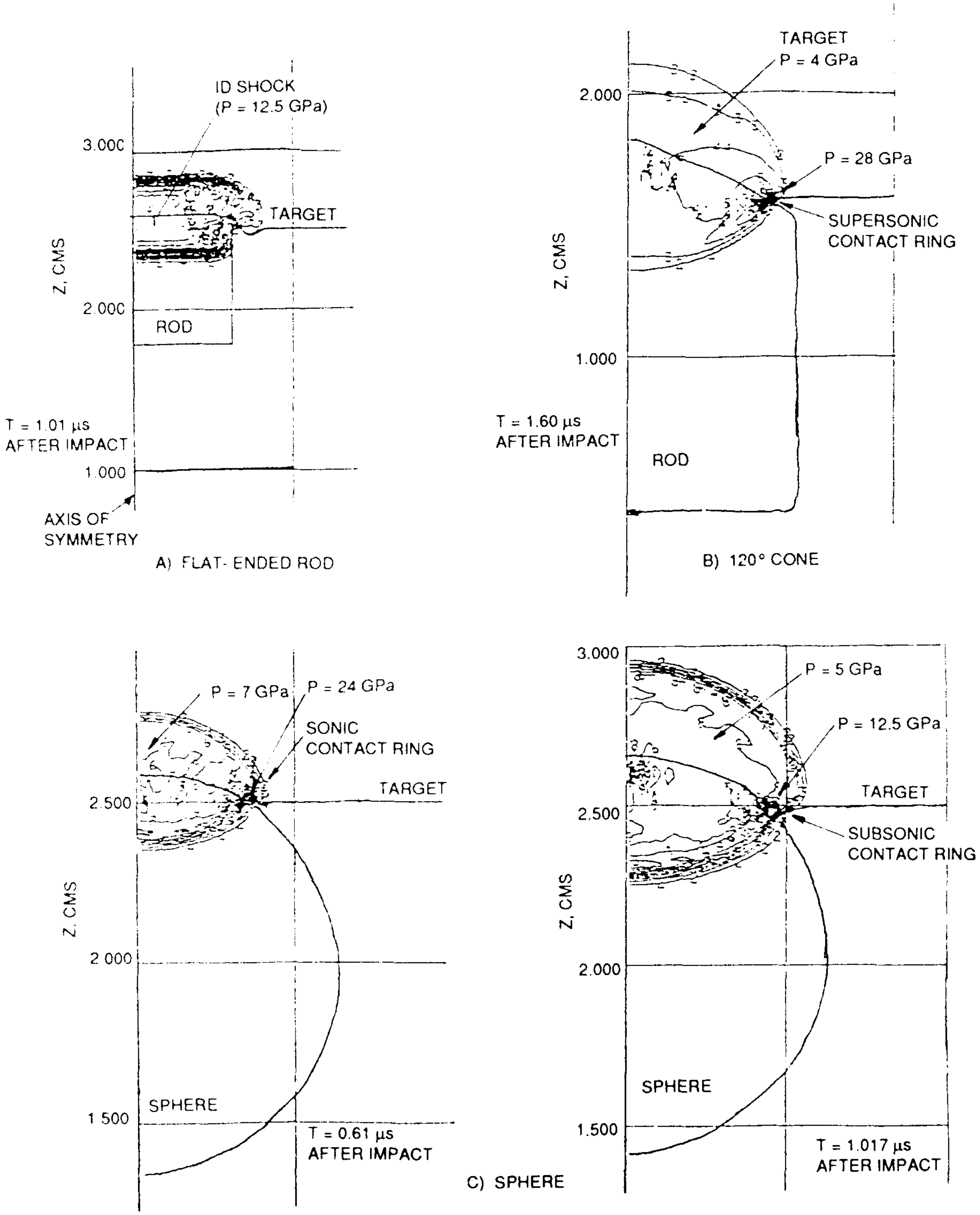

FIGURE 5. PRESSURE CONTOURS GENERATED BY IMPACT OF DIFFERENT GEOMETRIES OF STEEL PROJECTILE INTO BARE, UNREACTIVE EXPLOSIVE ($V = 1790$ m/s, $D_O = 12.6$ mm)

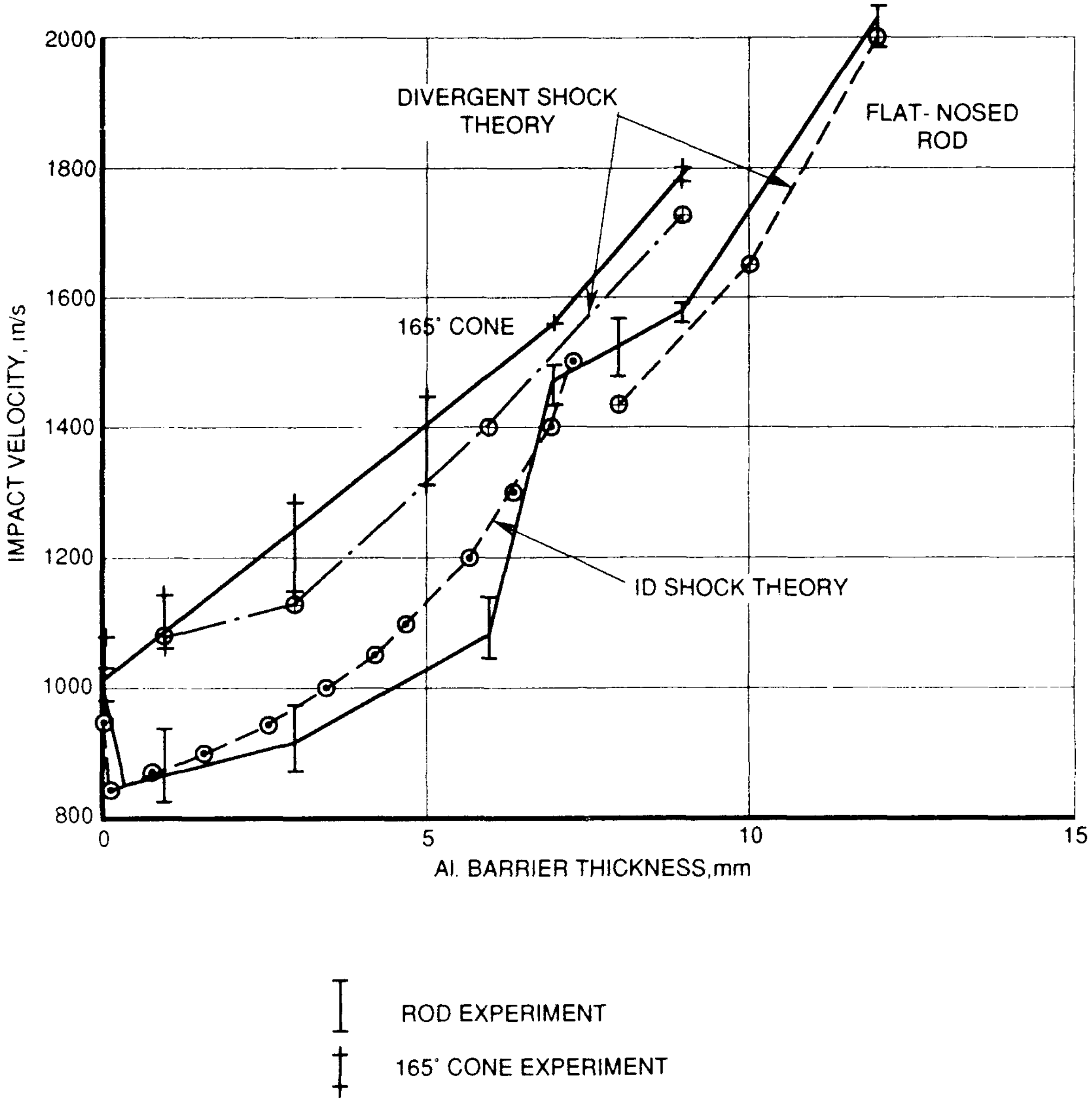

FIGURE 6. COMPARISON OF ID AND DIVERGENT SHOCK THEORY WITH EXPERIMENT

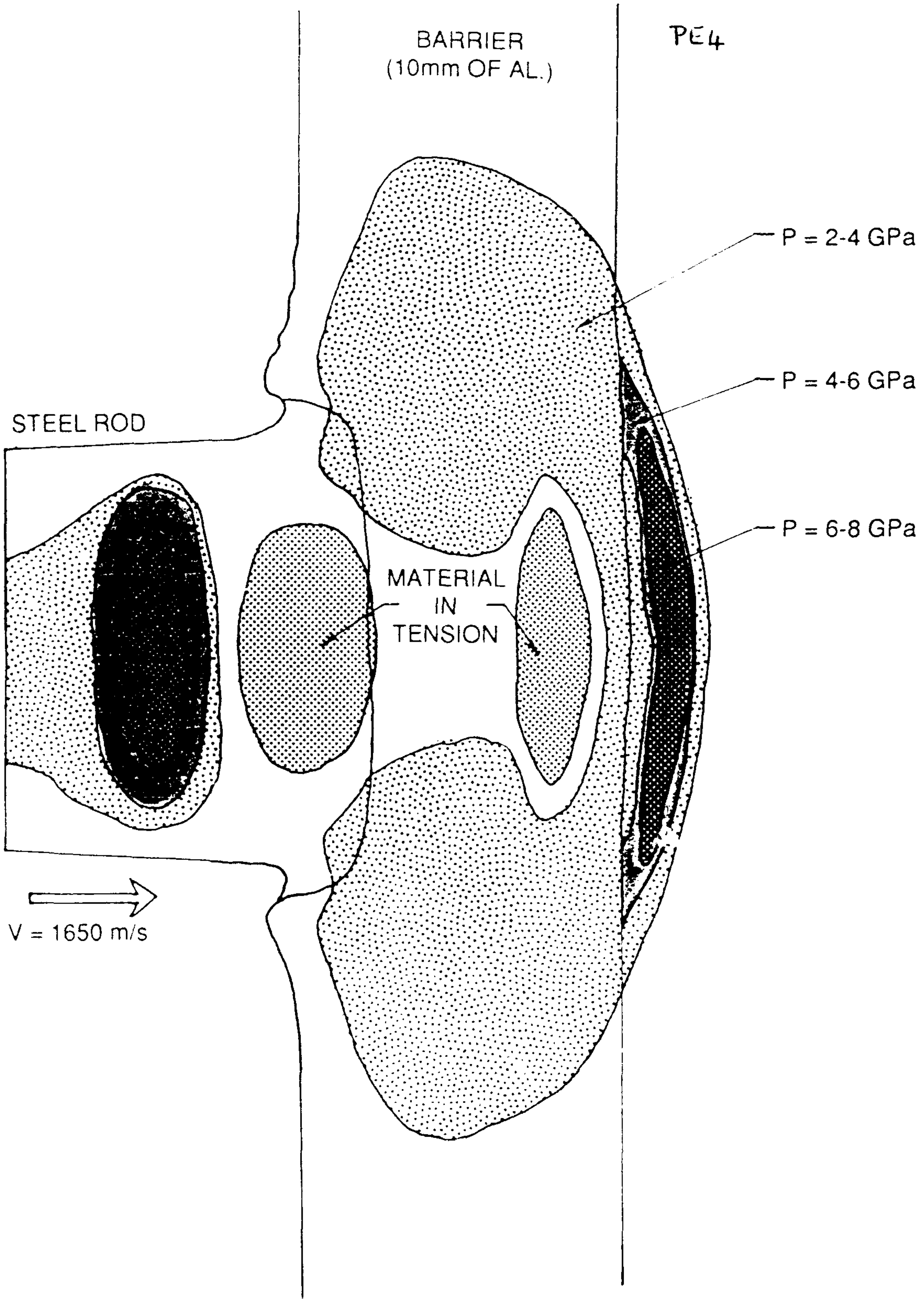

FIGURE 7. SIMPLIFIED PRESSURE CONTOUR MAP OF DIVERGENT SHOCK IN EXPLOSIVE (2 μs AFTER IMPACT) FROM 2D HYDROCODE PREDICTION

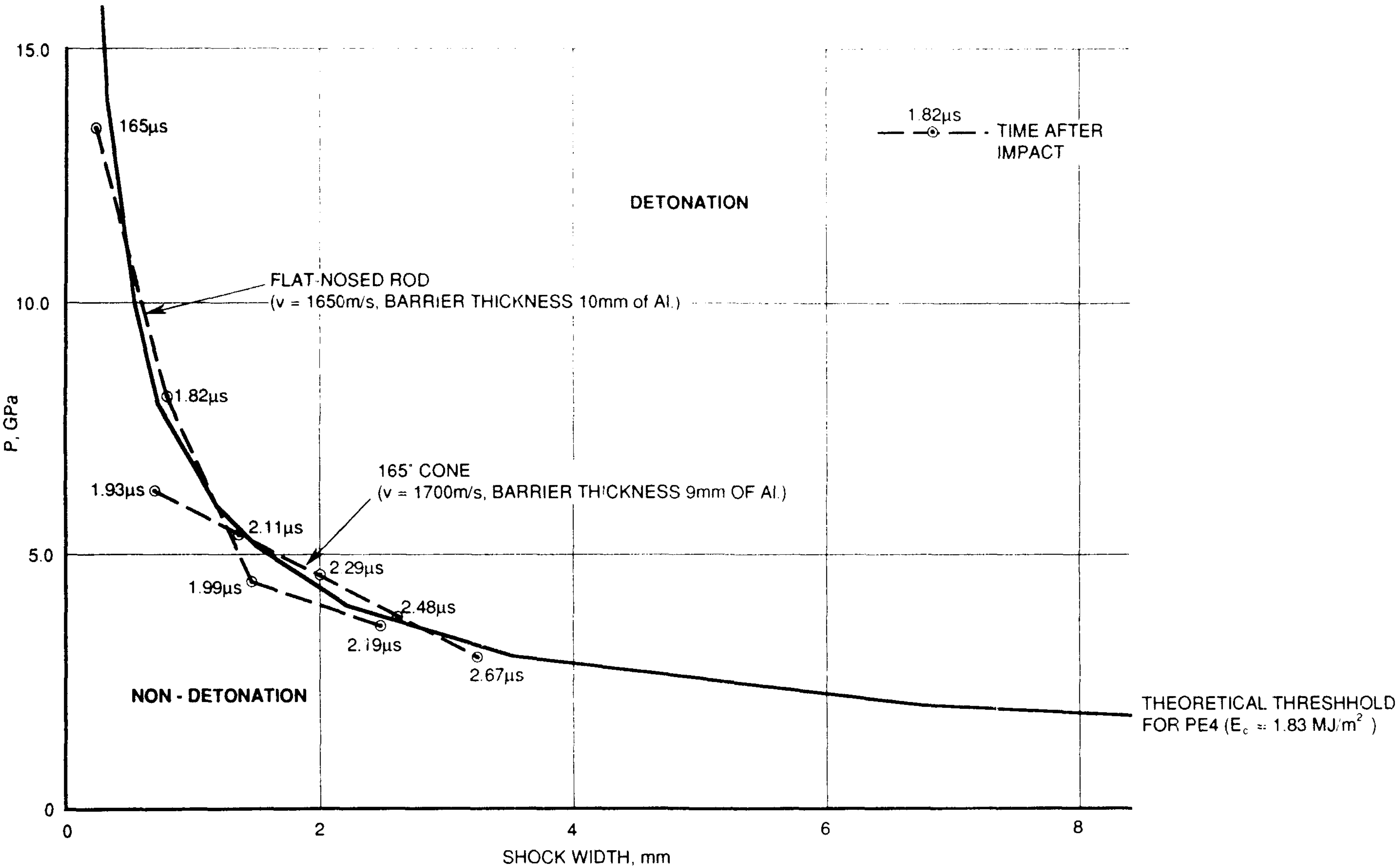

FIGURE 8. THEORETICAL THRESHOLD FOR PE4 AND ITS RELATIONSHIP TO IMPACTS FROM TWO TYPES OF PROJECTILES

Discussion

QUESTION BY ?: Did you ever think about a system of layers with varying impedances to decrease the sensitivity of ammunition?

ANSWER: That is an obvious possible consequence to this sort of thing, but the implication of what happens with aluminum barriers is that you can match or mismatch impedance.

FUEL FIRE AND BULLET IMPACT TESTS WITH WARHEADS

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The main requirements for insensitive ammunitions are the fast cook off or fuel fire test, the slow cook off test, the sympathetic detonation, the bullet and fragment impact and the shaped charge impact test (diagram 1).

The most common requirements are the fuel fire and the bullet impact test. The fuel fire test is performed by heating an original warhead in a vessel with kerosene. The warhead is equipped with a safety and arming unit.
The temperature of the high explosive surface inside the warhead increases to about 1000 °C.
Warheads filled with conventional compound B mixtures or other TNT bonded high explosive mixtures, cannot fulfill the fuel fire test. They start burning and later on a detonation occurs.

Regarding the heat conductivity and the coefficient of the thermal expansion, there is no visible influence between Comp. B, LX 14 and KS 32 (diagram 2), although they are PBX formulations.

The fuel fire safety is strongly influenced by the mechanical properties of the charge and the grain size distribution of the high explosive material in this charge.
In contrast to formulations with coarse material, formulations with a fine grain size are much more insensitive against fast cook off (diagram 3).

The tests carried out with different quantities of fuel and with or without a thermal insulation of the warhead, cause burning of the PBX charge in this big warhead ([illegible] kg high explosive charge) (diagram 4).

[illegible]

The fuel fire safety is dependent on the size of the warhead, i.e. it is no problem for very small warheads to fulfill the requirements of the fuel fire safety. The confinement of the warhead is a very important parameter; with a heavy confinement even PBX charges detonate. Best mechanical properties of the charge, i.e. a low Young modulus, a high [illegible] cracks, are required. The reason for the failure of TNT bonded charges in fuel fire tests are the bad mechanical properties. When the charge is heated up, you get a lot of small cracks with new burning surfaces. These surfaces cause high pressures and these pressures cause high burning rates. The result is the detonation of the charge (diagram 5).

Bullet Impact Test

Bullet impact tests are performed with a steel tube and filled with charges with different high explovive formulations. The firing is carried out on the cover plate centre (diagram 6).

Different formulations are tested for bullet impact tests. The caliber is half inch or 20 mm, the velocity is between 350 m/s and 1000 m/s. The charges have differnt Young modulus from 200 to 720 N/mm^2, different grain size distributions, different binder systems and, there is a small difference in the binder content.

Diagram 7 shows the great influence of the grain size distribution. This influence is more considerable than the influence of the Young modulus. Even with a Young modulus of 378 N/mm^2, the first formulation detonates with a low velocity of the bullet.

Another formulation with a high Young modulus of 720 N/mm^2 and high velocity of the bullet withstands the trial (diagram 7). After the test, the cover plate is pushed out and the high explosive is burned or just lying around.

This high energy formulation with 96 % of HMX withstands half inch and 20 mm caliber with a high velocity (diagram 8). Another formulation detonates with a bullet impact of half inch caliber (diagram 9).

Small changes in formulation are sufficient to withstand the bullet impact test (diagram 10). Tests with original warheads have the same results as tests in the small steel tube. A high Young modulus and a small content of the binder cause a detonation of the warhead (diagram 11).

Diagram 12 shows the results of the firing and the influence of the Young modulus as a feature for the mechanical properties. The brittle materials (for example PBX N5, LX 14, P 33) detonate with a high Young modulus with 400 to 1000 N/mm^2. Regarding the same grain size distributions, there is a limit for the detonation of about 350 N/mm^2. Above this point formulations detonate, below this point, they survive (diagram 12).

Conclusion:

Contemplating the bullet impact safety, there is a considerable influence of the ammunition caliber, the critical diameter of the high explosive, the confinement of the charge, the mechanical properties, the particle size distributions and the type of the binder (diagram 13).

Shaped Charge Impact Test

The toughest tests for a high explosive charge is the firing of a small or larger shape charge on the test sample. We are working with the trial set of diagram 14.

For these tests three different shaped charges with an outside diameter of 25, 33 and 44 mm are used. Regarding the smallest shaped charge, we can reduce the jet tip velocity to less than 2000 m/s with plates installed outside the copper cone (diagram 15 and 16). The tests were carried out with performace reducing plates, jet tip velocities of 3000 m/s, three different formulations with a binder content of 15 % and a solid content of 85 %.

These formulations show burning or no re-action, i. e. there is only a hole in the explosive sample (diagram 17).

There are also some formulations with a binder content of 15 % down to 5 % which do not react with shaped charges. PBX formulations of the first generation like PBX N3 and LX 14 detonate, although we used performance reducing plates and a low jet tip velocity of only 3000 m/s (diagram 18, 19).

Conventional high explosives have no chance in the shape charge impact test and also with 10 mm brass and 3000 m jet tip velocity, you get full detonation with compound B and SSM 8871 a Torpex type. It is necessary to reduce the jet tip velocity to 2000 m/s by means of additional plates, so that the charge can survive (diagram 20).

The tests carried out with the 44 mm shaped charge (diagram 21) show that the formulation can survive this threat of the 44 mm shaped charge impact.

Only the underwater formulation KS 57 withstands the shaped charge 44 with a jet tip velocity of 7800 m/s and reacts with violent burning (diagram 22).

Conclusion:

The vulnerability is considerably influenced by the formulation and the ingredients of the formulation, i. e. the binder, the high explosives and all other ingredients. The most important parameters for the binder are the mechanical properties, the aging and the coating behaviour. As far as raw materials are concerned, the grain size, the grain size distribution, the specific surface of the high explosive and the mechanical properties of the cristals are very important. Other ingredients, like plasticizers, antioxidants and catalysts, influence the mechanical properties of the charge . Bonding agents have a consi-derable influence on the coating behaviour and the mechanical properties (diagram 23).

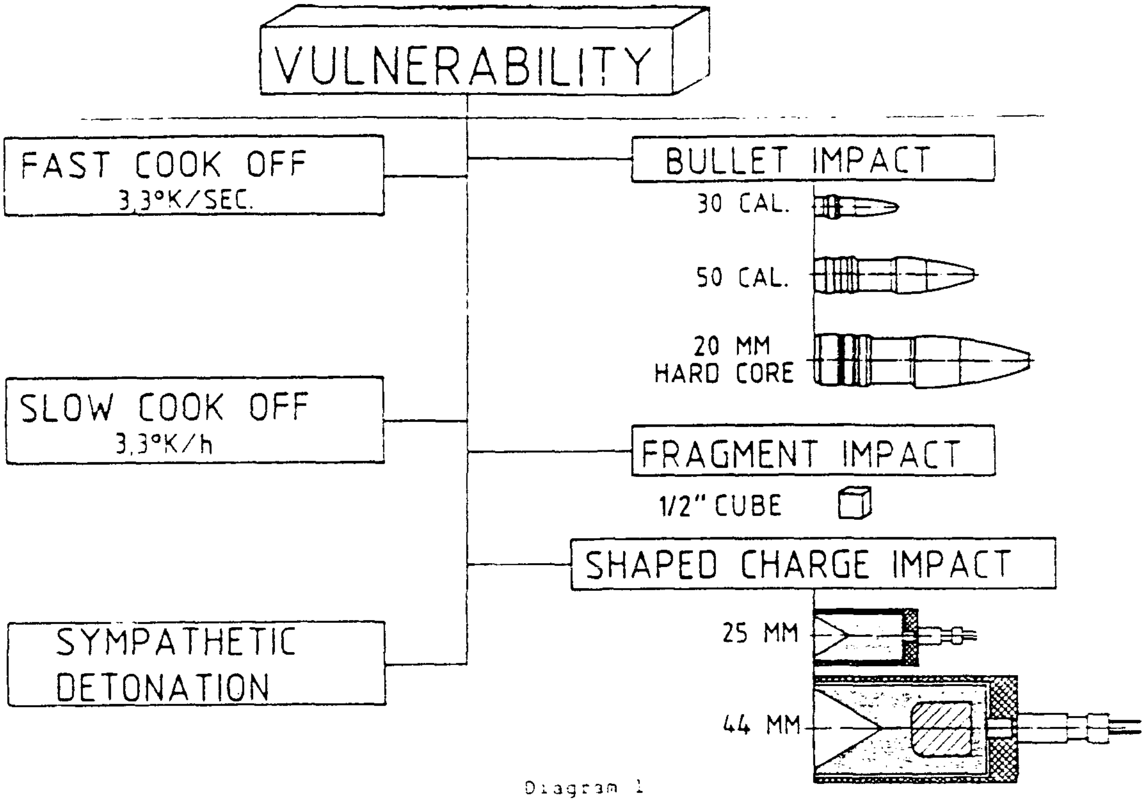


Diagram 1

Fuel fire

	TNT/RDX 25/70	LX 14	KS 32
Heat conductivity $\left[\frac{W}{cm \cdot K}\right]$	$3.4 \cdot 10^{-3}$	$4.39 \cdot 10^{-3}$	—
Coefficent of thermal expansion $[K^{-1}]$	$7.5 \cdot 10^{-5}$	$4.85 \cdot 10^{-5}$	$9.0 \; 10^{-5}$

Diagram 2

PBX-P

VULNERABILITY
FAST COOK OFF

HE TYPE	BINDER [VOL%]	HMX GRAIN SIZE c / f / uf	YOUNG'S MODULUS [N / mm2]	ELONGATION [%]	REACTION TYPE
P 31	8,00	2 1 -	246	1,05	BURNING RT 2
P 31 F	9,43	- 2 1	720	1,02	BURNING RT 1
P 32	7,95	2 1 -	378	1,63	DETONATION RT 5

Diagram 3

Fuel Fire

Fuel Type: Kerosene / Petrol

No. of Attempt	1	2	3
Amount of Fuel [l]	60 + 10	90 + 20	100 + 20
Thermal Insulation of Warhead	yes	yes	no
Time to Reaction [min]	> 13	17	8
Temperature on HE Surface	90°	failed	failed
Type of Reaction		Burning in case	Burning HE ejected

Diagram 4

Fuel fire

Influence on fuel fire safety

- Size of warhead
- Confinement
- Mechanical properties of HE-charge
  - ·Elongation
  - ·Tensile Strength
- Cracks

Diagram 5

Steel tube
for bullet impact trials

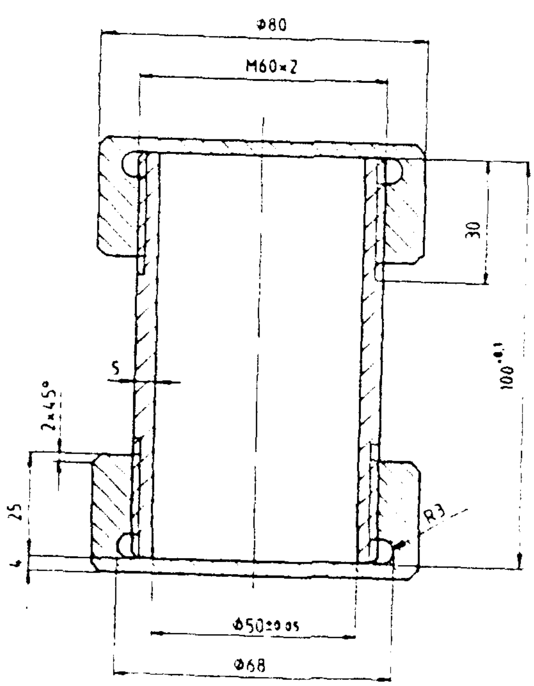


Diagram 6

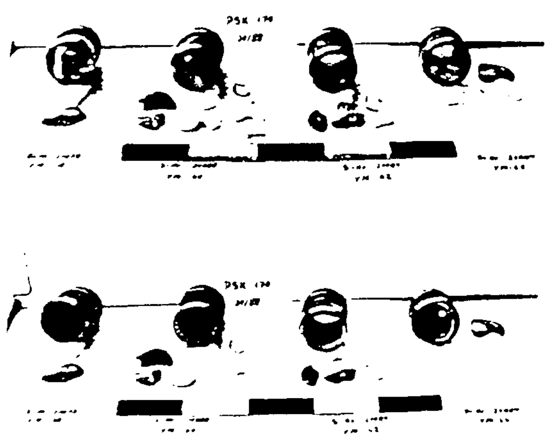
PBX P

Vulnerability
Bullet impact

HE Type	Binder Type	Binder [Vol %]	HMX Grain Size c/f/uf	Young's Modulus [N/mm²]	Elongation [%]	Density [g/cm³]	Caliber [mm]	V_s [m/s]	Reaction Type
P 32	PSK	7,95	2 1 -	378	1,63	1,796	12,7	353 597 908	Detonation Detonation Detonation
P 32 W	PSK/P	8,00	2 1 -	201	1,36	1,797	12,7	910 912	No reaction Mild reaction
P 32 W	PSK/P	8,00	2 1 -	201	1,36	1,796	20,0	1055	No reaction
P 31		8,00	2 1 -	246	1,05	1,801	12,7	596 912 915	No reaction No reaction Mild reaction
P 31		8,00	2 1 -	246	1,05	1,801	20,0	1057	No reaction
P 31 F		9,43	- 2 1	720	1,02	1,760	12,7	911	Mild reaction
P 31 F		9,43	- 2 1	720	1,02	1,760	20,0	1057	No reaction

Diagram 7

LOVA



PBX P 31

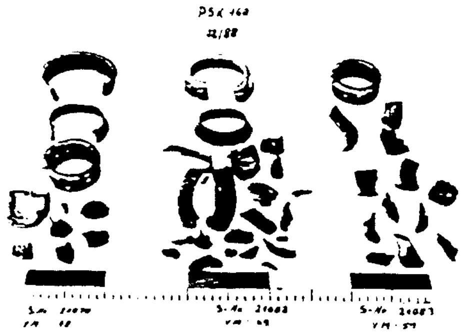
Bullet: Hard core

Caliber: 12,7 [mm]

Reaction: —

Diagram 8

LOVA



PBX P32

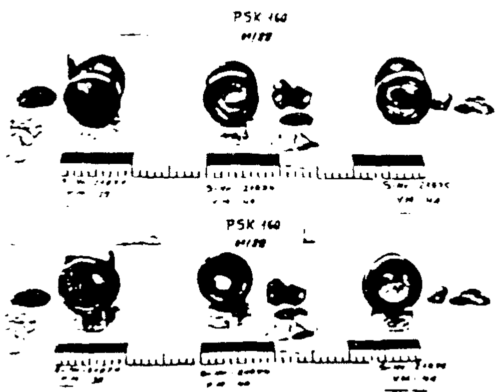
Bullet: Hard core

Caliber: 12,7 [mm]

Reaction: Detonation

Diagram 9

LOVA



PBX P 32 W

Bullet: Hard core

Caliber: 12,7 [mm]

Reaction: ——

Diagram 10

Bullet impact

Trials with original Warhead

Trial	Cal. (mm)	Velocity (m/s)	Charge	%Binder	Young modulus (N/mm^2)	Reaction
1	12,7	850	KS 22 RDX/Al/HTPB	15	24	No reaction
2	12,7	850	KS 32 HMX/HTPB	15	26	No reaction
3	20	1000	KS 32 HMX/HTPB	15	26	No reaction
4	20	1000	P 32 HMX/PSK	5	400	Detonation

Diagram 11

Youngs modulus

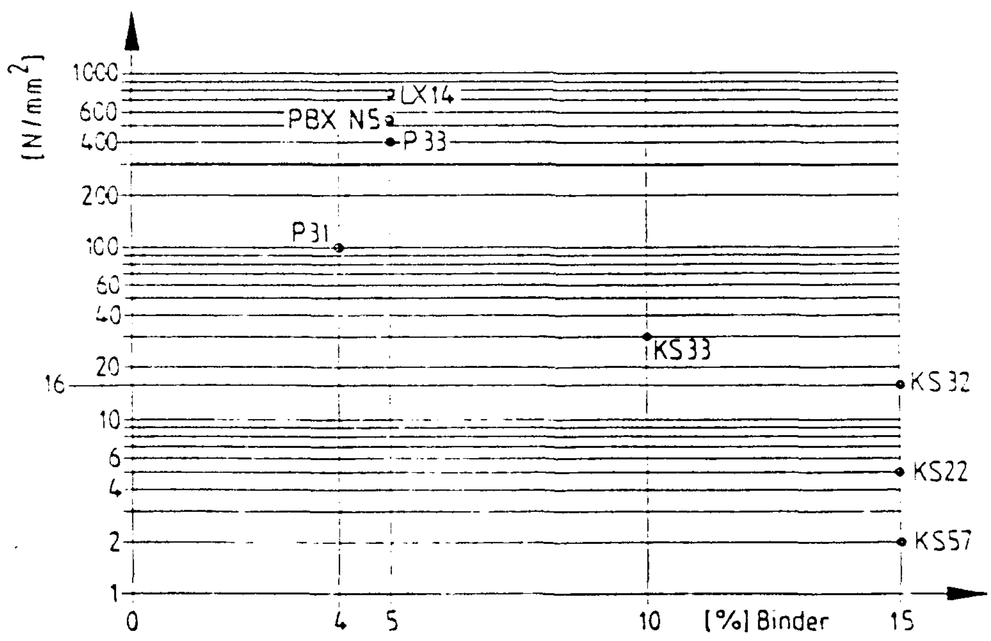


Diagram 12

Diagram 13

Bullet impact

Influence of

- Caliber
- Critical diameter
- Confinement
- Elongation
- Young's modulus
- Particle size
- Formulation

TRIAL SET

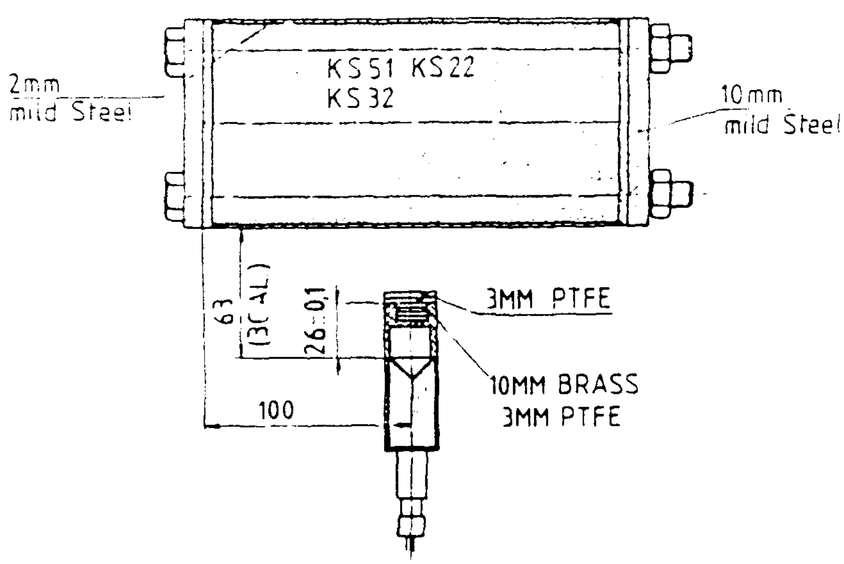


Diagram 14

VULNERABILITY

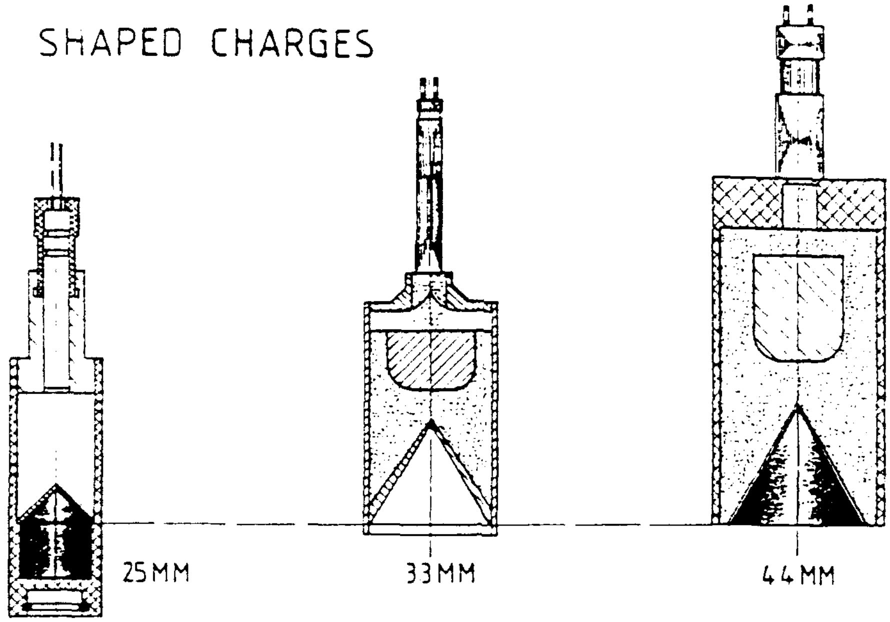
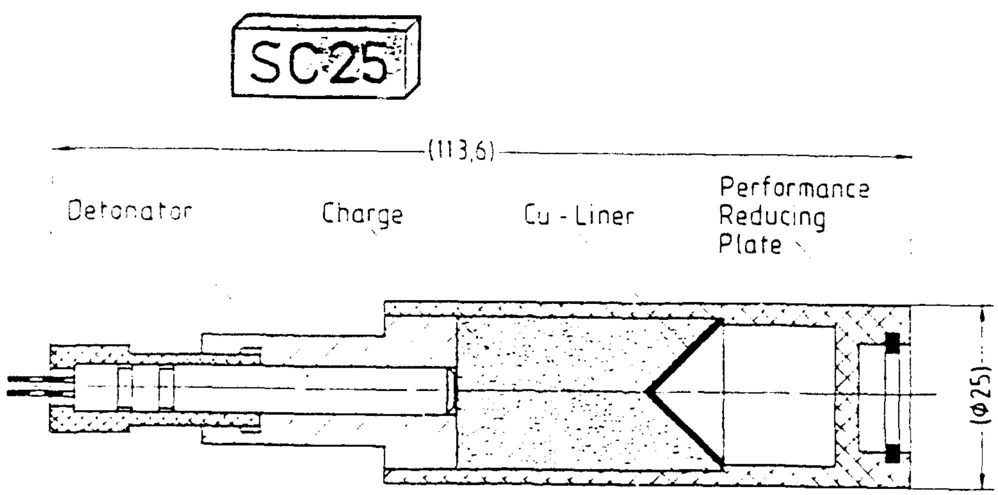


Diagram 15



Jet Tip velocity 5000m/s

Jet Tip velocity 20mm Brass + 2mm Steel) < 2000 m/s

Diagram 16

LOVA

SC25

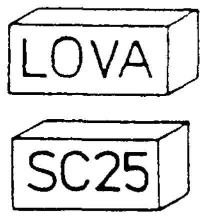
Trial	Charge (2kg)	Target	Performance Reducing Plates	Jet tip velocity [m/s]	Reaction
1	KS 51 AP/RDX/Al/HTPB	2mm Steel	10mm Brass +3mm PTFE	3000	Burning
2	KS 32 HMX/HTPB	2mm Steel	10mm Brass +3mm PTFE	3000	No Reaction
3	KS 22 RDX/Al/HTPB	2mm Steel	10mm Brass +3mm PTFE	3000	No Reaction

Diagram 17

SC 25

Trial	Charge (2kg)	Target	Performance Reducing Plates	Jet tip velocity [m/s]	Reaction
4	KS 32 HMX/HTPB	2mm St	—	5000	No reaction
5	KS 111 RDX/HTPB	2mm St	—	5000	No reaction
6	PBXN3 86/14 HMX/Nylon	2mm St	10mm Bass +4mm PTFE	3000	Detonation

Diagram 18



Trial	Charge (2kg)	Target	Performance Reducing Plates	Jet tip velocity [m/s]	Reaction
7	P 31 96% HMX 4% Binder	2 mm Steel	10 mm Brass	3000	Burning
8	LX 14 95% HMX 5% Binder	2mm Steel	10 mm Brass	3000	Detonation
9	P 31 96% HMX 4% Binder	2 mm Steel	———	5000	No. reaction

Diagram 19

Trial	Charge (2kg)	Target	Performance Reducing Plates	Jet tip velocity [m/s]	Reaction
10	Comp B	2mm Steel	10mm Brass	3000	Detonation
11	SSM 8871 (Torpex)	2mm Steel	10mm Brass	3000	Detonation
12	Comp B	2mm Steel	20mm Brass	< 2000	No. reaction
13	SSM 8871	2mm Steel	20mm Brass	<2000	Burning

Diagram [illegible]

TRIAL SET

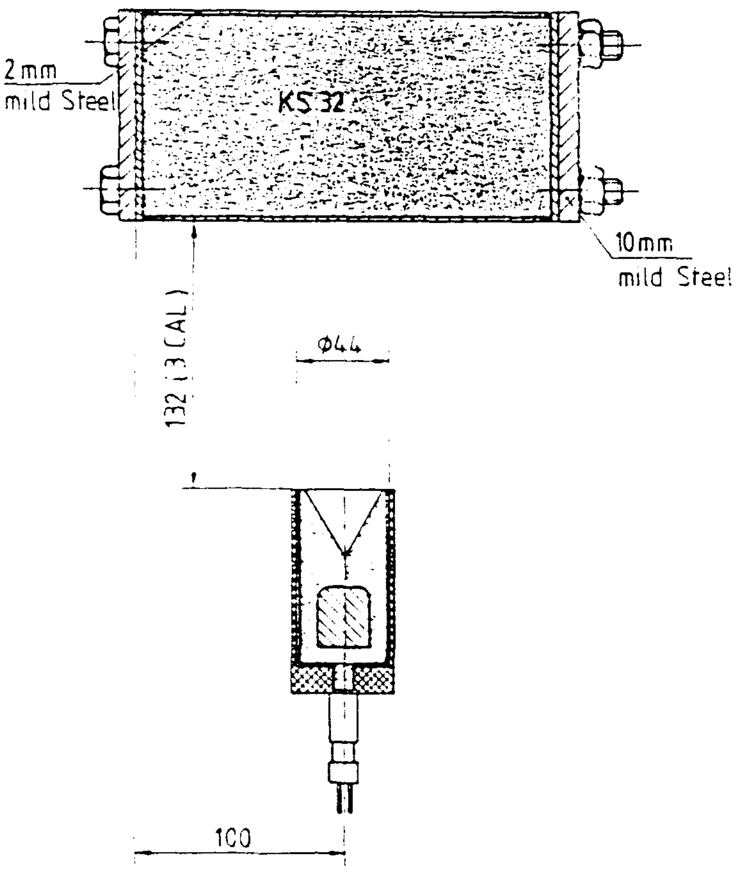


Diagram 21

LOVA

SC44

Trial	Charge (2kg)	Target	Performance Reducing Plates	Jet tip velocity [m/s]	Reaction
7	KS32 HMX/HTPB	2mm Steel	—	7800	Detonation
8	KS57/5 AP/RDX/Al/HTPB	2mm Steel	—	7800	Violent Burning
9	P31 96% HMX 4% Binder	4mm Steel	—	7800	Detonation

Diagram 22

VULNERABILITY

INFLUENCE OF FORMULATION

BINDER

- TYPE
- AGING
- OXIDATION
- EXSUDATION
- COATING BEHAVIOUR
- MECHANICAL PROPERTIES

HE

- TYPE
- GRAIN SIZE
- GRAIN SHAPE
- SPECIFIC SURFACE
- PURITY
- MECHANICAL PROPERTIES

INGREDIENTS

- PLASTICIZER
- ANTIOXIDANS
- CATALYST
- BONDING AGENT

Diagram 23

Discussion

QUESTION BY VICTOR, US: With the 25 mm shaped charge generator, what is the effect of the "performance reducing plate" on the jet diameter?

ANSWERED BY HELD: It reduces velocity and it increases the jet diameter by a factor of about 2.

THREE EFFORTS CONCERNING FRAGMENT AND SHOCK HAZARDS TO CASED MUNITIONS

by

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Research Department
Naval Weapons Center
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United States

1 SUMMARY

This paper is divided into three parts and describes the work being conducted by the Naval Weapons Center on the response of munitions to fragment impact. The first part described a methodology developed to model and analyze the response of munitions to fragment impact threats. The munition response levels within the model are divided into shock-to-detonation transition (SDT), burn-to-violent reaction (BVR), and no response. Part II of this paper describes the use of the wedge test for obtaining the SDT parameters necessary to accurately model and predict prompt detonation. If BVR is predicted, four basic response levels are possible. These are burn only, deflagration with or without propulsion, explosion and delayed detonation. Part III of this paper describes a planar rocket motor model developed to explore mechanisms related to the possible thresholds in the BVR regime.

2 PART I. METHODOLOGY FOR CONDUCTING FRAGMENT IMPACT ANALYSES

Martha Wagenhals, O. E. R. Heimdahl, Kenneth L. Woods, and Eric Lundstrom

2.1 INTRODUCTION

A methodology has been developed for conducting fragment impact analyses of munitions in their storage/stowage configurations. The objective of the methodology is to determine if the munition will respond adversely to any specified impact threat, and if so, how much shielding is required to prevent the adverse response. The elements of the methodology have been computerized and housed on a VAX™. This paper presents the current status of the methodology, describes the step-by-step approach and presents an example problem.

The methodology has been formalized in a computer code named FRAGMAP, which stands for Fragment Impact/Munition Response Analysis for Guidance in Mitigation Assessment Program. FRAGMAP is an interactive computer program which implements our approach for assessing the likelihood of the detonation, or lesser response, of a cased munition due to fragment impact, and the effectiveness of selected mitigation measures. The code is written in VAX™ FORTRAN, and uses the DISSPLA® plotting package. FRAGMAP provides a means for storing fragment threat, munition response and barrier material data. It manipulates these data in a systematic manner and presents the calculated solutions in forms of tables and plots. Secondarily, the program computes the probability of shock-to-detonation transition (SDT) as a function of distance for far field fragment impact situations.

2.2 THE FRAGMENT IMPACT PROBLEM

The fragment impact problem is depicted in Fig. 1. There is a fragment source. It can be the detonation of a hostile missile, or one of our own stores. Usually there are barriers between the fragment source and the munition of concern. The barriers can be any combination of shipping containers, decks, bulkheads, or magazine walls. The actual threat that reaches a munition is degraded by the penetration process, resulting in loss of fragment mass and velocity. There are also entrained plate fragments from the various barrier perforations. We want to know if the residual threat will cause the impacted munition to respond, and if so, at what level: detonation, burn-to-violent reaction or burn only. The steps involved in applying the primary portion of our methodology are as follows.

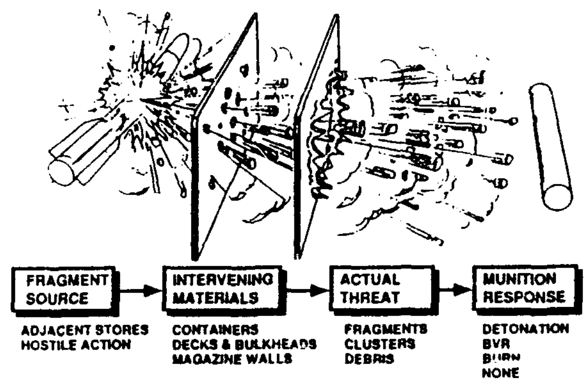

Fig. 1. The Fragment Impact Problem.

a. determine the response thresholds of the munition of concern,
b. determine the undegraded impact threat characteristics in terms of fragment mass and velocity,
c. determine which fragments from the specified threat will cause the unprotected munition to detonate, or cause some lesser response,
d. determine an equivalent spaced array for all barriers intervening between the fragment source and the munition (i.e. container walls, bulkheads, etc.),
e. determine the residual mass and velocity character of the threat fragments after perforation of the intervening barriers,
f. determine if the residual threat will cause a detonation or some lesser response,
g. estimate what additional shielding is required to mitigate any adverse response.

2.3 ELEMENTS OF FRAGMAP

2.3.1 Response Plots. The first response considered is prompt detonation. Prompt detonation is defined as the shock to detonation transition (SDT) regime. If prompt detonation doesn't occur, then lesser responses are possible. Figure 2 shows the assumptions behind the responses considered.

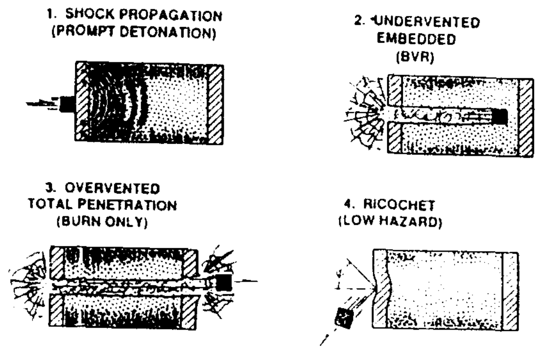

Fig. 2. Response Mechanisms.

The burn-to-violent-reaction (BVR) response is dependent upon many factors. The most violent response in this regime occurs if the fragment becomes embedded, and case confinement is not relieved. A milder response occurs (burn only) when a fragment passes completely through the munition, and provides sufficient venting to release the pressure buildup of the explosive reaction.

We have defined a low hazard or no response regime as that which occurs when a fragment ricochets. The assumption is that any fragment having insufficient energy to penetrate the case will not cause any reaction. We realize that this assumption does not hold true for all energetic materials.

The different response regimes and thresholds are indicated in Fig. 3 for a specific example acceptor munition. The shock-to-detonation (SDT) threshold for the specified munition is determined using hydrocode calculations of fragment impact (Ref 1). Reaction of the energetic material is predicted by the Forest Fire burn model (Ref 2), which is calibrated using wedge test data. The boundary for the low hazard/no response regime is the ballistic limit of the case material. We substitute the ballistic limit threshold for the ignition threshold of the energetic material due to the ease of computing ballistic limits. Between these two thresholds is the burn-to-violent reaction (BVR) zone.

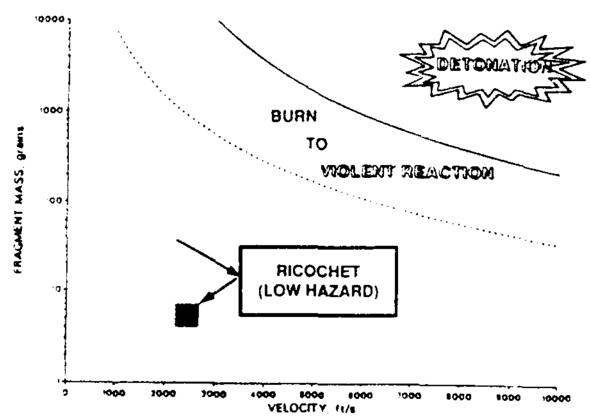

Fig. 3. Response Plot.

2.3.2 <u>Coupling Threat and Response</u>. The fragment threat is generally obtained from warhead arena test characterization data. An overlay of the threat upon the response plot generated for a specific weapon identifies which fragments can cause a detonation, which can cause some response, and which can not penetrate the case.

Figure 4 shows the fragment distribution of a selected donor weapon overlaid onto the response plot of Fig. 3. The size of the circles indicates the number of fragments having a given mass and velocity. The large circle above the prompt detonation line represents about 1000 fragments. The circle indicating the greatest mass represents 30 fragments. We will use these two fragments in an example later. The square shown represents the 250 grain, 8300 fps cube fragment used for the NAVSEA insensitive munitions fragment impact test (Ref 3) Only those fragments falling above the solid line will cause this specific munition to detonate. A large number of fragments fall in the BVR zone, including the 250 grain cube. The majority of fragments from this donor munition will not cause any reaction, individually, if they strike the acceptor munition. This methodology is for single fragment impact. We are currently conducting a parametric study to implement a multiple fragment impact capability in the methodology. We are also working on other improvements, which will be discussed later.

Figure 4 serves to identify which fragments from the chosen threat which have a potential to cause our acceptor munition to respond adversely. The next step is to select a barrier that will prevent the various possible responses.

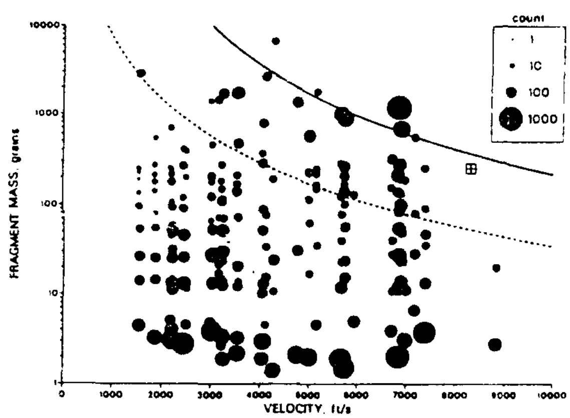

Fig. 4. Overlay of a Fragment Threat Map onto Response Plot (Fig. 3).

2.3.3 <u>Residual Threat/Mitigation Calculations</u>. Two different sets of equations are used to estimate the residual threat after penetration of existing barrier materials. These are the JMEM (Joint Munitions Effectiveness Manual (Ref 4)) penetration equations (also referred to as Thor equations) and FATE (Ref 5) (Fast Air Target Encounter) equations. Once the residual threat is defined, the munition response is estimated. Adverse response prevention requirements are then established by an iterative process.

Figure 5 shows the residual fragment threat of Fig. 4 after passing though a 1/4-inch thick steel plate, as calculated using the Thor penetration equations. These equations indicate that a 1/4-inch thick steel plate will drop all but one of the fragments below the threshold for a prompt detonation. The initial and residual 250 grain cube are also shown. It has dropped below the ballistic limit velocity of the case, and should cause no hazard to this munition. A lot of small fragments are stopped completely, and no longer show on the plot.

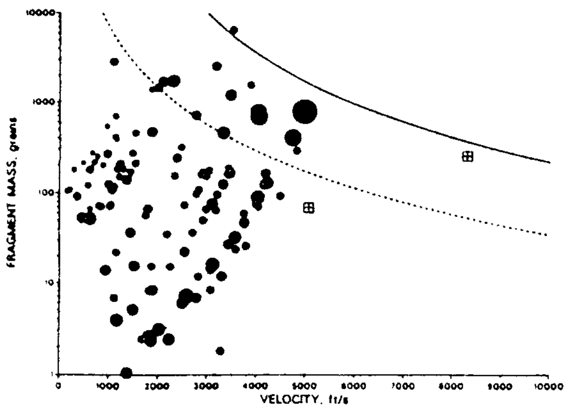

Fig. 5. Residual Fragment Threat After Passing Through a 1/4-inch Thick Steel Plate Using Thor Equations.

The Thor equations are the result of curve fits to experimental data from an Army test program (Ref 6). These equations follow the largest part of the fragment through the penetration process. They do not permit an estimate to be made to be made of plate debris nor secondary fragments which have broken off the original fragment from either erosion or shatter. Steel fragments are known to shatter on impact above some velocity threshold.

Figure 6 also shows the residual fragment threat of Fig. 4 after passing though a 1/4-inch thick steel plate, but calculated using the FATE penetration equations. The results are significantly more complex. While the FATE equations are also for single fragment impact, they do account for fragment shatter and plate debris. In this case, the dark circles represent the primary residual fragment from the original fragments. The unfilled circles represent secondary residual fragments from the original fragment when it met the shatter criteria. The open square symbols represent entrained plate fragments from the penetration process. The initial and residual 250 grain cube are also shown. The FATE equations indicate that a 1/4-inch thick steel plate will drop all of the fragments below the threshold for a prompt detonation. The penetration process does create some additional hazardous fragments though, as noted by the residual secondary fragments (unfilled circles) falling above the dashed line representing the ballistic limit velocity threshold. The FATE equations are also empirical equations, based on Navy and contractor tests. While they are still for single fragment impact, they do account for fragment shatter and plate debris. The residual threat is a curve fit of data, and shatter thresholds were established by actual firings.

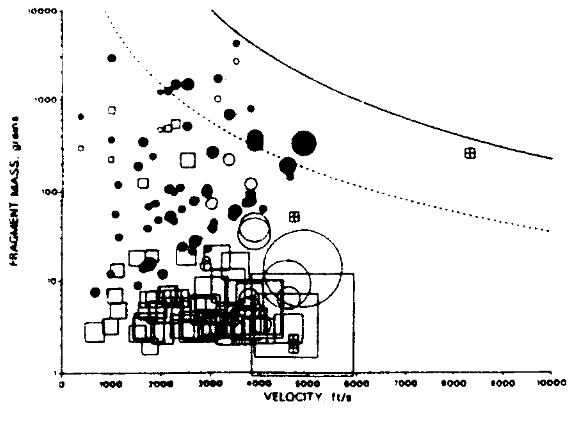

Fig. 6. Residual Fragment Threat After Passing Through a 1/4-inch Thick Steel Plate Using FATE Equations.

2.4 EXAMPLE PROBLEM.

For the example problem, we have selected the two fragments from the donor weapon shown in Fig. 4 which are considered to be the greatest hazard to the acceptor munition. The first fragment is large (6,659 grains) and somewhat slow, travelling about 4,260 ft/sec. The characterization data used indicated there are about 30 of these fragments, and they are from the 55-60 degree polar zone. (Most munitions have a longitudinal axis of symmetry which is taken as the polar axis. Polar angles are then measured through the center of the munition. The nose end is designated zero degree, and the tail 180 degrees. An interval between two specified polar angles is defined as a polar zone.) The second fragment has a mass of 1,168 grains and is travelling at an average velocity of 6,830 ft/sec. There are about 1,066 of them, from the 80-85 degree polar zone of the dono: weapon. The 1/2-inch cube is also shown. As noted previously, the 1/2-inch cube will not cause this particular munition to detonate, but the two example fragments will.

In examining the fragment threat, it was felt that if the munition could be protected from the two selected fragments, it would be protected from all of the fragments from the specified donor. As such, any barrier design recommendations are predominantly based on this portion of the analyses. Figure 7 shows the response plot of Fig. 3 overlaid with the initial conditions of the two selected fragments. The 1/2-inch cube is also shown. The next step is to apply both the Thor and FATE equations to these two fragment families and determine what thickness of steel is required to protect the vulnerable munition.

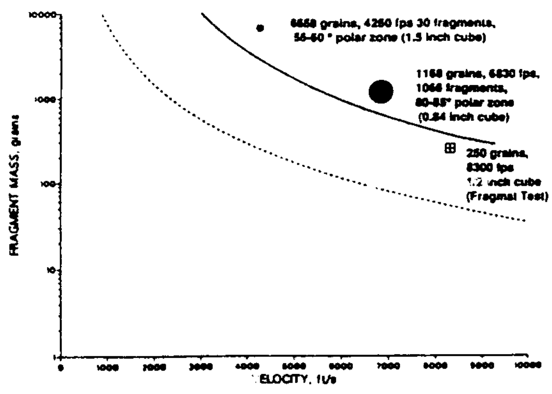

Fig. 7. Two Threat Fragments Overlaying the Response Plot of Fig. 3.

Figure 8 shows the degradation of the selected fragments as different thicknesses of steel plate are entered into the analysis using Thor equations. The original dots are plotted, and then the residual fragment after passing though a single plate. Plates evaluated were 1/32, 1/8, 1/4, 1/2, 1/ and 2 inches thick. Figure 8 indicates that a 1/4-inch thick steel plate is required to drop the 1,168 grain fragment below the detonation threshold, but it required a 1/2-inch thick plate to bring the large 6,659 grain fragment out of the detonation zone. A 1/4-inch thick plate takes the 1/2-inch cube completely out of the hazard zone. To completely protect this munition, a 2-inch thick plate of steel would be required. However, a 1-inch thick plate would protect it from 99% of all the fragments from this specific threat. A solution based on the Thor equations is the most conservative.

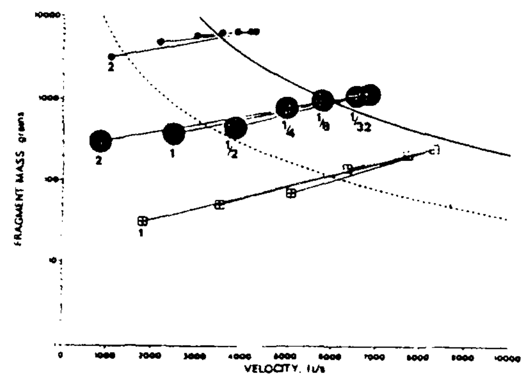

Fig. 8. Degradation of Example Fragments as a Function of Barrier Thickness Using Thor Equations.

Figure 9 shows the analysis using FATE equations. As you can see, there is a significant difference in the results. While Thor predicts that a minimum of 1/4-inch of steel is required to bring the 1,168 grain fragment below the detonation threshold, FATE says that a 1/32 inch thickness will suffice. The difference is that the FATE equations predict that the thin plate will shatter this fragment. Notice that the thicker plates actually produce smaller mass losses than the 1/32 inch plate. This is due to suppression of the spall phenomena during penetration. According to FATE, the 6,659 grain fragment still requires a 1/4-inch thick steel plate as a minimum to bring it below the detonation threshold. The 1/32-inch thick plate appears to drop the 1/2-inch cube fragment completely below any hazard zone.

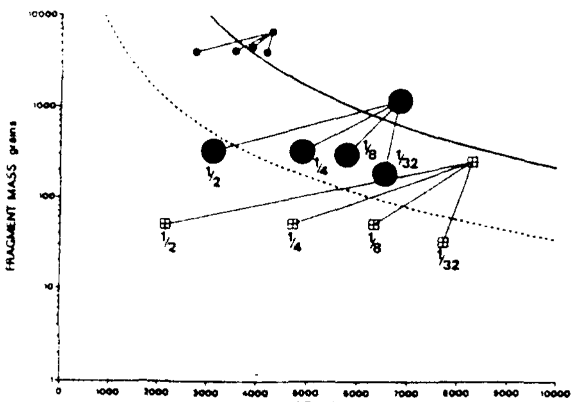

Fig. 9. Degradation of Example Fragments as a Function of Barrier Thickness Using FATE Equations.

The results from the FATE equations indicate that a spaced array armor design could be quite effective as a light weight barrier solution, provided that the specific environment has enough room for such a design. To make a final recommendation regarding a barrier design, one would have to evaluate the hit probability and other factors which are possible with our methodology, but which are not presented due to paper length restrictions.

2.5 LIMITATIONS TO THE METHODOLOGY

2.5.1 Response Model Limitations. The reactive model used for the response plot SDT threshold requires wedge test data for the energetic material. Wedge tests are expensive and only work for relatively simple, sensitive explosives and propellants. Most propellants are very complex energetic materials and have more than one inherent reaction rate. A model and a calibration method is needed for handling such complex materials.

The response model is currently limited to single fragment impact with axisymmetric shapes. In real situations, the munition will be struck multiply, by irregular fragments. A more sophisticated response model able to account for the effects of both multiple impacts and the irregular impactor shapes is essential.

2.5.2 Barrier Model Limitations. Both Thor and FATE are limited as analyses tools. Both equations only permit steel fragments. If a donor were made of titanium or some metal other than steel, viable penetration equations do not exist. With respect to barrier materials, Thor offers a choice of 17 different materials, including steel and aluminum. FATE only offers steel and aluminum.

2.6 OVERCOMING LIMITATIONS

There are ways for overcoming these limitations. However, they are generally expensive. It requires lots of test data against lots of different materials. Initial efforts are directed towards analytical studies. Experimental testing will be needed in the future to verify the analytical results.

2.6.1 SDT Predictions. To successfully model the response of any energetic material, wedge test data is required for lots of explosives. Wedge test data is specifically needed for the Forest Fire Burn Model used in our calculations. Gap tests and other sensitivity data are helpful in trying to approximate burn models based on similar materials for which there is wedge test data. For the more complex energetic materials, a model and a calibration method needs to be developed.

2.6.2 Fragment Shape Study. The SDT threshold is calculated for idealized fragment shapes, either a cylinder or a sphere. The velocity threshold for a sphere is approximately twice that of a cylinder with the same diameter. Most real fragments are neither cylinders nor spheres, but are more of a strip segment shape. Two fragment shapes which can be modelled with a 2-dimensional hydrocode are a cylinder and a strip. Any intermediate impactor shape, (one that could contain the cylinder and be contained in the strip), should exhibit SDT behavior bounded by these two simpler shapes. The objective of the fragment shape study is to compare the SDT behavior of cylinders and strips in order to obtain limits for more realistic shapes.

2.6.3 Multiple Fragment Impact. As noted earlier, a parametric study using the MESA (Ref 7) 2-dimensional Eulerian hydrocode is being conducted to establish a multiple fragment impact criteria for determining when a fragment acts independent of its nearby neighbors, and when the neighbors have to be taken into consideration. The initial study is limited to rod impactors in order to utilize the 2-dimensional code. Small scale testing is planned to validate the multiple fragment impact model that is being developed.

2.6.4 Overcoming Barrier Model Limitations. For penetration effects, different materials need to be used as the impactor against materials already calibrated, and more barriers need to be calibrated.

2.7 FUTURE WORK

2.7.1 FRAGMAP. A cutoff point has been selected and Version 1.0 of the FRAGMAP code is currently being documented. As a minimum there will be a users manual and the source code. A formal report is planned which will discuss the assumptions and theories behind the various elements of the methodology. At this time, FRAGMAP has had a limited number of users. Therefore, although the program has been used extensively, it may still contain errors,

incongruities and other unpleasant surprises. The current version is considered developmental. Distribution of the code will contain appropriate warnings.

2.7.2 Response Model Refinements. Further work will be done overcoming the limitations described above. This includes completing the analytical studies on multiple fragment impact, and fragment shapes. Experimental verification of the analytical studies in planned using small scale testing techniques.
Within the general community, work is being done to develop a model to handle the response of complex explosives and propellants to shock stimuli. Some of this effort is being done at the Naval Weapons Center. As such models become available, they will be incorporated into FRAGMAP.

2.7.3 Barriers. A new version of the FATE equations is expected imminently. As soon as it is available, it will be incorporated into FRAGMAP. An experimental effort is needed to develop equations for impactors (fragments) other than steel against existing barriers, and for steel and other impactors against additional barriers. Complex barriers such a compo .e armors and the new generation of potential armor materials need to be evaluated and calibrated for use in codes.

2.7.4 Stacking Configurations. A means for modelling sympathetic detonation bombs stacks is being developed. The initial work is being done using the MESA 2-D hydrocode on a Cray computer. Significant work has yet to be done to make the model a reality, but initial results are very promising.

2.8 POTENTIAL APPLICATIONS

The methodology shown can also be used in reverse for designing insensitive munitions. If you have the necessary data, you can examine the effects of case thickness and energetic material selection on the vulnerability of your weapon. The results can also be used to select test parameters for verifying the protection provided against actual threats, for obtaining needed materials data, and for verification and validation of our models. A similar approach can be used for conducting sympathetic detonation analyses.

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3 PART II. WEDGE TEST FOR STUDYING SDT IN PROPELLANTS.

Allen J. Lindfors

3.1 INTRODUCTION

A series of minimum smoke propellants were developed at the Naval Weapons Center to have reduced shock sensitivity (Ref 1). These propellants were specifically designed to replace current conventional minimum signature propellants. These conventional propellants contain as much as 67% of high explosive (HMX or RDX) in nitrate ester plasticized energetic binders, which are known to be shock sensitive materials.

Three basic techniques were used to reduce the shock sensitivity of the propellants. These included using low shock sensitive energetic materials such as ammonium nitrate (AN) increasing the level of homogeneity by reducing density discontinuities, and reducing the level of participation of the HMX or RDX in the shock to detonation reaction.

To explore the shock sensitivity of these propellant formulations, the wedge test was conducted. The wedge test series were conducted on propellant samples incorporating different formulation variables. The variables included, type of high explosive (RDX or HMX), and with and without high density burn rate modifiers. The wedge test sensitivity of these propellants were then compared to a conventional minimum signature propellant.

3.2 PROPELLANT FORMULATIONS

The basic propellant formulation consisted of RDX or HMX, AN, nitrate ester plasticized energetic binders, and other additives. All the formulations contained 60% by weight of solids. The first formulation used RDX, as the high explosive material, and lead carbonate as a burn-rate modifier. The second formulation consisted of HMX, minus the lead carbonate. The third and final propellant contained RDX, also minus the lead carbonate. The propellants were processed using small particle size solids and mixed extensively under a vacuum to minimize density discontinuities. The resulting formulations were of very good quality and 99% of theoretical maximum density.

Typical propellant compositions contained 60% by weight of solids which included 15%-17% of 1.4 micron HMX or RDX, and 43%-45% of 40 micron AN. Nitrate ester plasticized energetic polymers were used as binders, and for the purpose of this study 0.8% of 3.7 micron lead carbonate was added as a burn rate modifier.

3.2 WEDGE TESTING

3.2.1 Wedge Test Description. The wedge test is a method by which the shock initiation characteristics of an energetic material may be determined. A planar shock wave is introduced into the explosive to be tested. As the shock progresses through the explosive it generates hot-spots, in a heterogeneous material, that build-up to a detonation.

The objective of the wedge test is to determine the run to detonation point at which the detonation wave overtakes the shock wave. This point is characterized by a unique time and distance to detonation for a specific set of input conditions.

A streak camera is used to record the wedge test event. The surface of the wedge is mirrored to reflect light into the camera. When either the shock wave or detonation wave reaches the surface, the surface distorts so that the light is no longer reflected into the camera. As the detonation wave overtakes the shock wave the slope of the reflected light trace on the film changes. Thus, the run to detonation point can be determined from the film record. A schematic of the wedge test set-up is shown in Fig. 1.

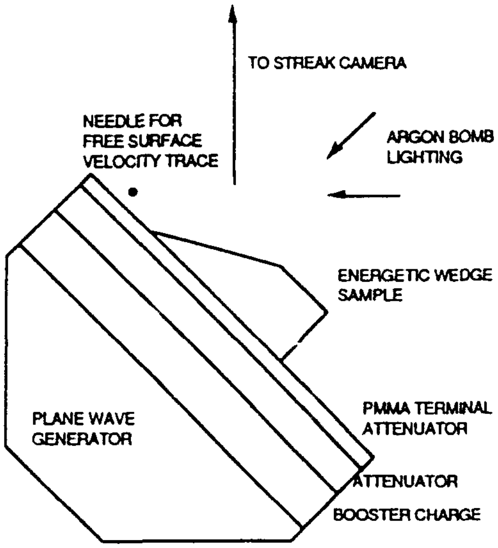

Fig. 1. Schematic of the Wedge Test Set-Up.

The results of a series of wedge tests are usually presented as plots of input pressure versus distance to detonation and time to detonation. With these plots energetic materials may be compared with regard to relative sensitivity. This is done by assuming that for a given distance to detonation, the energetic material that requires the lower input pressure to achieve this distance is the more sensitive.

It should be noted though, that this is just one test for sensitivity and the relative sensitivity rankings between energetic materials may vary for different tests. For example, the Naval Ordnance Laboratory Large Scale Gap Test may give markedly different sensitivity rankings for the same energetic materials, as compared to the wedge test.

3.2.2 Wedge Test Set-up. As shown in Fig. 1, a planar shock wave is introduced into the energetic wedge sample. The input shock wave pressure is varied to achieve different run-to detonation points

3.3 WEDGE TEST DATA REDUCTION

The streak camera records were first examined qualitatively for exposure, planarity of the incoming shock, position and time of the transition to detonation, and the presence of any secondary shock reverberations that could affect the results. A schematic of a streak camera record is shown in Fig. 2. The film records were subsequently digitized on an optical comparator. The required parameters for reduction of the film data, in the order they were analyzed, are outlined in subsequent sections.

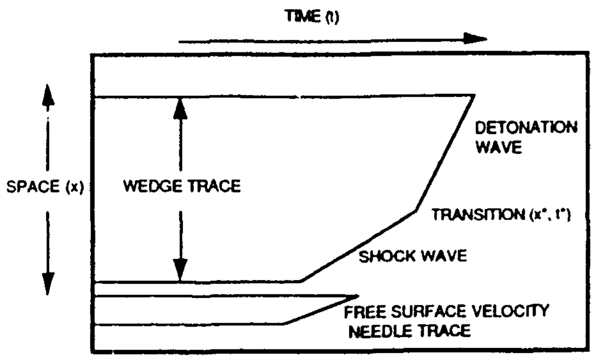

Fig. 2. Schematic of a Wedge Test Streak Camera Record.

3.3.1 Free Surface Velocity. To determine the input conditions at the terminal attenuator/propellant sample interface, one needs to measure the free surface velocity ($U_{f.s.}$) of the terminal attenuator. This is done by watching the reflection of the needle off the mirrored surface move towards the actual needle. By knowing the viewing angle (fixed at 45 degrees), the magnification, and the camera writing speed, the free surface velocity can be determined using the following equation:

$$U_{f.s.} = U_c \tan A / 2M \sin 45$$

where

U_c = camera writing speed (mm/μs)
A = angle formed between moving image and real needle
M = magnification

The film records of the wedge traces were typically read in 0.250 or 0.500 mm increments along the time axis. They were converted to real times using the relation:

$$t = Y_f / U_c$$

where

t = real time (μsec)
Y_f = incremental film time (mm)
U_c = camera writing speed (mm/μs)

3.3.2 Space-Time Data. The film space data associated with the time readings were reduced using a similar triangles method (Ref 2). In this method one needs only to know the actual wedge height and measure the total film trace width to convert film space to real space. The data are converted using the equation:

$$X_r = (W_h / W_f) X_f$$

where

X_r = real space (mm)
W_h = wedge height (mm)
W_f = wedge film trace width (mm)
X_f = film trace measurements (mm)

3.3.3 Transition To Detonation and Shock Velocity. The transition to detonation is assumed to occur at the region of maximum acceleration along the film trace, and is designated (x*,t*). These points were read directly from the film records. While this determination can be somewhat subjective in the case of materials which exhibit "smeared out" transition regions, the propellants tested in these experiments showed very well defined transition regions.

To determine the initial shock velocity (U_{s_0}) in the energetic wedge sample, a plot was made of incremental average velocities (x/t) versus time (t) up to the transition point. Inconsistent data points at the ends of the trajectory were discarded. The data were then fitted, by a least squares method to the relation:

$$x = U_{s_0} t + 1/2\, bt^2$$

where

x = real space (mm)
t = real time (µsec)
b = acceleration of shock wave (mm/µs^2)

The derivative, with respect to time, evaluated at $t = 0$ is taken as the initial shock velocity.

3.3.4 <u>Shock Properties</u>. To determine the shock Hugoniot of the energetic material only two parameters are needed. These are the shock velocity in the terminal attenuator and the shock velocity in the energetic material. To determine the shock velocity in the terminal attenuator one needs to know its particle velocity and its shock Hugoniot. The particle velocity in the terminal attenuator is found by assuming that it is one half of the free surface velocity. The shock Hugoniot for Plexiglass (Ref 3) has been well defined by:

$$U_s = 2.598 + 1.516\, U_p$$

Since the shock velocity in the energetic material is known from the film records, the particle velocity and initial pressure in the energetic material can be found using the impedance matching technique. This technique gives rise to the equations:

$$P_e = [Z_a \cdot Z_e / (Z_a + Z_e)] \cdot U_{f.s.}$$
$$U_{p_e} = [Z_a / (Z_a + Z_e)] \cdot U_{f.s.}$$

where

P_e = pressure in energetic material (GPa)
Z_i = shock impedance = $U_{s_i} r_{o_i}$
U_{s_i} = shock velocity (mm/µs)
r_{o_i} = Initial density (gm/cc)
U_{p_e} = particle velocity in energetic material(mm/µs)
$U_{f.s.}$ = free surface velocity of terminal attenuator (mm/µs)

3.4 EXPERIMENTAL RESULTS

The results of the wedge tests performed are listed in Table I. The formulation designations are as follows. RDX-$PbCO_3$ indicates the RDX based propellant with the lead carbonate burn rate modifier, HMX indicates the HMX formulation without the lead carbonate, and RDX is the same as RDX $PbCO_3$ minus the lead carbonate.

3.5 SHOCK HUGONIOTS

From the shock velocities and the calculated particle velocities the shock Hugoniots are given below, and the plots in the Us-Up plane are shown in Figure 3.

RDX-PbCO3	Us = 1.44 + 3.04 Up
HMX	Us = 1.77 + 2.02Up
RDX	Us = 2.61 + 1.65Up
HEP 2	Us = 2.45 + 1.61Up

Results of an earlier wedge test series on a high energy minimum signature propellant, (HEP 2), which contains 67% HMX-RDX, and nitrate ester plasticized binder, are listed in Table II for comparison purposes (Ref 4).

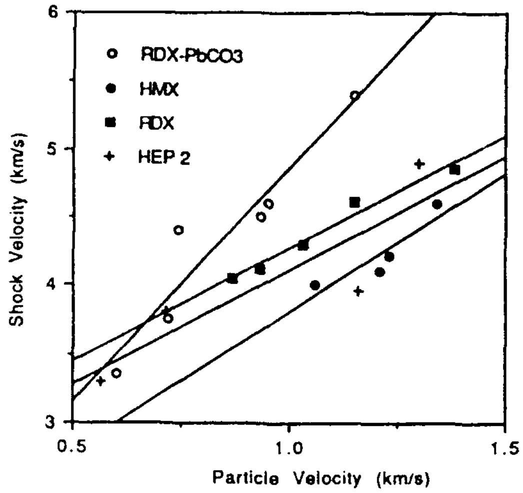

Fig. 3. Shock Hugoniots of the Propellants Tested in the Us-Up Plane.

3.6 SHOCK SENSITIVITY

The traditional method for plotting the data from the wedge test is known as the Pop-plot after Alfonso Popolato. Popolato found that over a range of input pressures, log-log plots of run to detonation, or time to detonation versus pressure, are linear. The equation of the Pop plot over the linear range, in run to detonation versus pressure form, is then:

$$\log x^* = A + B \log P$$

In this form P is in gigapascals, x* is in millimeters, and A and B are determined from a least squares fit in the log-log plane. Similarly, time to detonation versus pressure takes on the same form with different constants.

For the propellants tested, Pop-plots of distance to detonation versus input pressure are shown in Fig. 4. As can be seen, at low input pressures the Pop-plot becomes non-linear and pressure approaches a vertical asymptote. This implies that a different type of mechanism is controlling the reactivity and this will be discussed further in the subsequent section.

Table I. Wedge Test Results

Propellant	U_{s_o} (mm/µs)	U_{p_o} (mm/µs)	P_o (GPa)	r_o (gm/cc)	x* (mm)	t* (µs)	$U_{f.s.}$ (mm/µs)
RDX-$PbCO_3$	5.40	1.15	10.00	1.60	1.50	0.22	2.92
RDX-$PbCO_3$	4.60	0.95	7.04	1.60	6.25	1.25	2.33
RDX-$PbCO_3$	4.50	0.93	6.73	1.60	9.60	1.96	2.26
RDX-$PbCO_3$	4.40	0.74	5.40	1.60	11.47	2.49	1.90
RDX-$PbCO_3$	3.75	0.72	4.35	1.60	-----	-----	1.68
RDX-$PbCO_3$	3.35	0.60	3.20	1.60	-----	-----	1.37
HMX	4.60	1.34	9.98	1.623	1.54	0.27	3.05
HMX	4.21	1.23	8.41	1.623	12.10	2.48	2.76
HMX	4.10	1.21	8.10	1.623	13.52	2.87	2.70
HMX	4.01	1.06	6.90	1.623	14.32	3.11	2.39
RDX	4.85	1.38	10.70	1.60	11.71	2.46	3.18
RDX	4.62	1.15	8.48	1.60	13.72	2.96	2.70
RDX	4.30	1.03	7.11	1.60	15.30	3.31	2.40
RDX	4.12	0.93	6.18	1.60	17.73	3.93	2.17
RDX**	4.05	0.87	5.65	1.60	-----	-----	2.03

* Indicates Transition to Detonation
** Indicates No Transition to Detonation

Table II Wedge Test Results for a Minimum Signature Propellant, (HEP 2).

HEP 2 Shot #	U_{s_o} (mm/µs)	U_{p_o} (mm/µs)	P_o (GPa)	r_o (gm/cc)	x* (mm)	t* (mm)	$U_{f.s.}$ (mm/µs)
1	4.90	1.30	11.46	1.70	1.56	0.32	3.28
2	3.30	0.562	3.11	1.68	20.87	5.85	1.30
3**	-----	-----	-----	1.69	-----	-----	-----
4	3.80	0.713	4.52	1.67	5.26	1.59	1.70
5	3.96	1.16	7.73	1.68	2.35	0.552	2.60

* Indicates Transition to Detonation
**Indicates a No Data Shot.

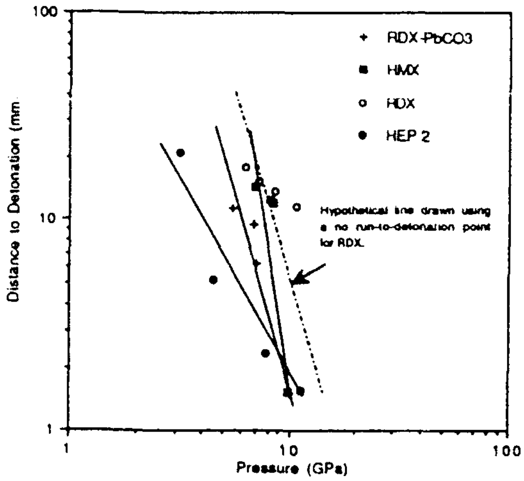

Fig. 4. Pressure Versus Run for Insensitive Propellants and HEP 2.

The interpretation of sensitivity behavior of an energetic material using these plots is done by observing the behavior of the constants A and B for the propellants tested. In Fig. 4 the Pop-plots for RDX-$PbCO_3$, HMX, RDX, and HEP 2 are shown. The intercept value A defines the horizontal positioning of the Pop-plot; thus it defines the shock region of interest, and B is the slope of the line.

Hence, a propellant with a higher pressure intercept and steep slope would be less sensitive compared to a second propellant with lower pressure intercept and shallower slope. Therefore, from Figure 4, it can be seen that RDX-$PbCO_3$, HMX, and RDX are all less sensitive than HEP 2.

For two propellants with different intercepts but very similar slopes the propellant with the higher pressure intercept is less sensitive at all pressures compared to the propellant with the lower intercept. This can be seen in Fig. 4 when we compared RDX-$PbCO_3$ to HMX, and HMX to RDX.

3.6 DISCUSSION

In general, all of the propellants have steep Pop-plots. Thus, the run to detonation will occur only over a very small pressure region. From an experimental stand point this small pressure region makes it very difficult to gain a variety of run distances. For example the pressure difference required for a 1.5 millimeter run and a 12 millimeter run is only 1.5 GPa for the HMX formulation.

However, from an shock insensitive propellant stand point, this type of behavior is desirable. This is due to the fact that if a propellant is going to detonate it should only occur at fairly discrete high pressures, as is the case for these propellants.

The relative low shock sensitivity of these propellants is attributed to three basic factors. First, the amount of high energy explosive, HMX or RDX, was reduced from 67% to 15%-17%, the remainder being replaced with AN. This has the overall effect of reducing the shock sensitivity of the propellant because AN is much less sensitive to shock than RDX or HMX. The other two factors involved the reduction of density discontinuities and thus the number of hot-spots initiated. This was the result of the RDX or HMX being present in small particle size, (2μm), and eliminating the high density, (6.14 gm/cc) lead carbonate burn-rate modifiers

The reduction of AN participation in the detonation reaction can be seen from the Pop-plots. In the RDX-$PbCO_3$, formulation containing the lead carbonate, the Pop-plot is well behaved and is linear until the run to detonation does not occur. In fact if one were to plot the "no go" point it would lie on the same line. However, in both the HMX and RDX formulations, at approximately 7.5 GPa, there is a distinct change in the Pop-plot that is quite consistent for both formulations. In the work of Stinecipher (Ref 5) on composite explosives, the partial AN reaction was attributed to intermolecular reactions in the detonation zone of only a thin layer of the AN. In this work however, it is suggested that further participation of the AN can be induced by higher shock pressures or high density discontinuities.

3.7 SUMMARY

The shock sensitivity of several propellants were assessed in the wedge test. The results indicated that these propellants are much less shock sensitive than the conventional minimum smoke propellants. This paper also included a study of the effect of various formulation variables on the shock sensitivity of this type of propellant composition.

This study provided much guidance in tailoring the formulation for further reducing the shock sensitivity of these materials. The results indicated that the use of shock insensitive filler (AN),and increasing the degree of homogeneity (use of fine particles of high explosive), minimized the physical discontinuities and reduced the shock sensitivity of minimum smoke propellants. These studies also led to some insights into the level of participation in the shock to detonation reaction of certain components of energetic composite materials.

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4 PART III. PLANAR ROCKET MOTOR TEST MODEL

Stephen A. Finnegan, Jan C. Schulz and J. Kenneth Pringle

4.1 INTRODUCTION

Bullet or fragment impact against a solid rocket motor can cause a reaction ranging from mild burning to detonation. Prompt detonation may occur immediately on contact through the mechanism of shock-to-detonation transition (SDT). Delayed reaction (either burning or detonation) may occur at later times. Delayed reactions are believed to be associated with damage and fragmentation of propellant during penetration; however, the underlying mechanisms are not well understood.

Study of delayed reaction phenomena is complicated by the fact that these processes occur within the motor case. A planar rocket motor test model has been developed as an aid in visualizing these processes. This model consists of a steel plate, a layer of propellant, an air gap, a second layer of propellant, and a second steel plate, as shown in Fig. 1. A degree of confinement is provided by the addition of transparent Plexiglas sidewalls. The open architecture of the model allows impact and reactions within the bore (air gap) to be photographed.

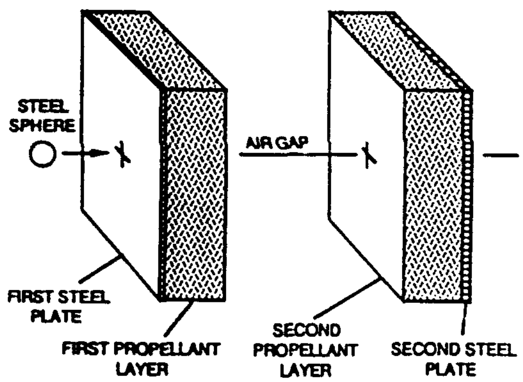

Fig. 1. Planar Rocket Test Model.

The basis for this test model was the observation, made from impact tests using inert simulant, that a "bubble" of propellant debris forms at the rear of the first propellant layer as a result of projectile perforation of the layer. As the bubble expands longitudinally into the adjacent air space, it elongates and eventually breaks into fragments. The presence of a closely spaced second propellant layer inhibits breakup and leads to the formation of "shredded appearing" debris (Ref 1).

Planar rocket motor test model results show that ignition of bubble debris occurs upon impact with the second propellant layer followed by a reaction ranging from mild burning to delayed detonation, depending on the type of propellant and the width of the air gap (Ref 2). Further studies, including hydrocode modelling, show that the ratio of air gap distance to bubble breakup elongation is an important factor in determining the type and intensity of reaction that occurs (Ref 3).

The present paper reviews the work done to date on energetic materials using the planar test model. In addition to summarizing previous work, it also discusses results from current efforts.

4.2 HYDROCODE STUDY

A parametric study of the debris bubble expansion and breakup process was conducted using an Eulerian hydrocode, CSQ III. The study was performed to establish the basic character of the debris bubble and to establish breakup trends as a function of various target and impact parameters. Parameters varied included impact velocity, propellant layer thickness, and plate material. Runs were made against "half targets" only; impact against a second propellant layer was not considered.

The output of each hydrocode run consisted of a sequence of computer plots showing deformed cross-sections of the projectile and target layers at constant time intervals. An example is shown in Fig. 2. At 30 μs the projectile has perforated the plate and is penetrating through the propellant layer. By 60 μs a bubble has started to form at the rear surface of this layer. The layer elongates, thins down and starts to break up at some time prior to 150 μs. The plots indicate that the debris bubble can be regarded as an expanding hollow shell, similar to those occurring in hypervelocity impacts (Ref 4). The exterior shape closely matches that seen experimentally at distances out to 3-4 inches (Ref 2).

From the computer plots, debris bubble elongation as a function of time and at breakup can be determined. An analysis of the computer runs for the various parameters studied showed that breakup elongation increases with impact velocity, propellant layer thickness, and plate density (Ref 3). (A comparison between hydrocode-calculated elongation measurements and experimentally-measured elongation values and reaction limits is presented in a later section of this paper.)

It should be pointed out that the debris bubble is not a spall. A spall is the result of tensile failure when a shock wave is reflected back into the material as a rarefaction at a free surface. Bubble formation in the present case is a much longer term process produced by the mechanical interaction of the projectile with the propellant layer. This is clearly shown by the modelling results. A comparison of initial shock pressures in the propellant (determined by impedance matching) with hydrocode-calculated breakup elongation values for various case materials also shows no correlation, indicating that the initial shock is not responsible for breakup of the bubble (Ref 3).

4.3 EXPERIMENTAL SETUP

Energetic materials used in the various studies included two conventional aluminized, one reduced smoke HTPB/AP, and four minimum smoke propellants along with one explosive (Composition B). Of these, two (reduced-smoke HTPB/AP and one high-nitramine, minimum-smoke material) were tested extensively and the others to a more limited degree.

For comparability, the thickness of the propellant layers and cover plates (1 1/2 and 1/16 inches, respectively) were held constant. Hardened (370 BHN) steel was generally used for the first (impact side) cover plate, while mild (95 BHN) steel was often used for the second (exit side) plate, particularly in latter tests. Latter tests also included some involving uncovered (bare) propellant. Initially, the air gap was varied between 1/4 and 7 inches. As it became apparent that the most violent reactions occurred at air gaps below 3 inches, that value became the upper limit for most subsequent tests. Projectiles were mostly 3/4-inch-diameter mild steel spheres, although 3/4-inch-diameter ogival-nosed cylinders were used for two tests.

Projectiles were fired from a 20 mm smooth-bore powder gun. The velocity range for testing was 2000-4600 ft/s;

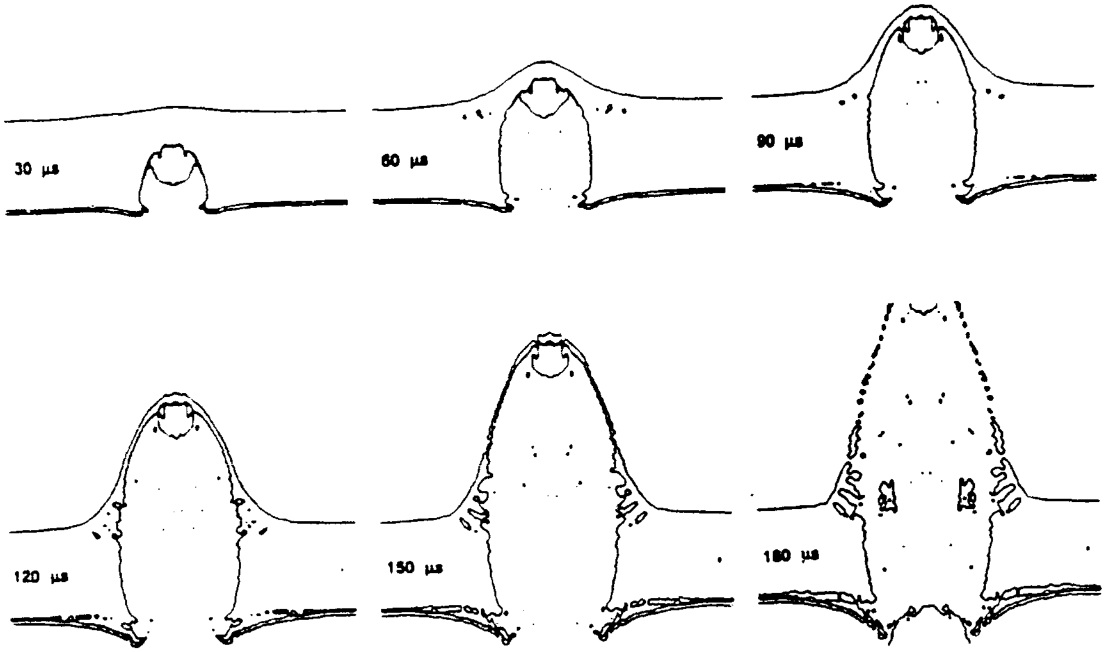

Fig. 2. Hydrocode plots for 3/4 inch steel sphere impacting 1 1/2-inch propellant layer with 1/16-inch steel cover plate at 3800 ft/s.

however, most testing was done at velocities between 3600 and 4000 ft/s. Projectiles were sabotted for launching. Those for spherical projectiles were designed to separate during flight and be stopped by a stripper plate; those for ogival projectiles were rigidly attached to provide greater stability during flight and target penetration. In-flight projectile velocities were measured using a Photec high-speed camera running at 16,000 frames/s in conjunction with a backlighting system consisting of a diffusing screen and light source (initially sunlight and reflecting mirror, later an array of flash lamps). Impact processes and propellant reactions were observed using a Fastax high-speed camera running at 32,000 frames/s along with a separate, similar backlighting system.

Targets were initially enclosed by Plexiglas sidewalls. However, an analysis of delayed detonation reactions indicated that most occurred too early after impact of the bubble for pressure buildup due to confinement to be a factor in initiation. After this was confirmed by tests of unconfined targets, later tests were done without these enclosures.

4.4 EXPERIMENTAL RESULTS

The main data source from each test was the film record from the high-speed camera. Space limitations prevent these from being shown in this paper. Instead, major events (e.g., ignition and reaction patterns) are shown in a series of sketches made from the film records. Photographic records can be found in a previous report (Ref 2). Results for impacts involving violent burning and impacts involving delayed detonation are discussed in the following two sections.

4.4.1 __Burning Reaction__ As shown in Fig. 3, ignition of bubble debris first occurred upon impact with the second propellant layer. (Tests of "half targets", i.e., with the second propellant layer removed, showed no ignition of bubble material for expansion distances up to 12-18 inches. Bubble debris was also safely captured in cotton-batting-filled containers.) In all cases, ignition appeared to be associated with impact of the projectile rather than impact of bubble debris. No ignition attributable solely to impact of bubble debris on the second propellant layer was observed.

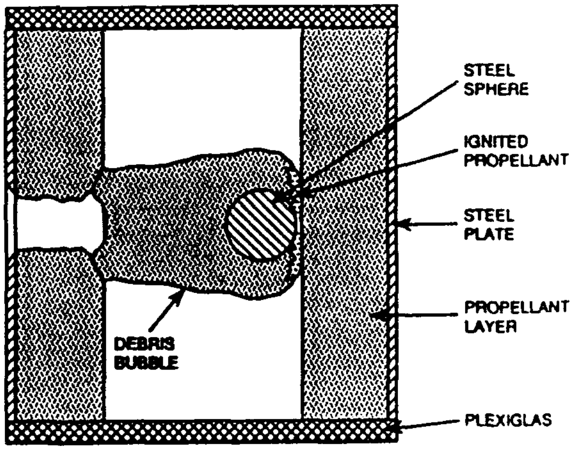

Fig. 3. Sketch of Debris Bubble Ignition Process.

For most propellants, ignition of bubble debris was followed by a burning reaction that propagated outwards from the center of the impact area. Two kinds of burning reactions were observed depending on the width of the air gap. An intense reaction, found at smaller air gaps (generally below 3 inches), was associated with debris flowing outwards along the impact surface, as sketched in Fig. 4. In this situation, the debris bubble appeared to be opaque (unbroken) prior to impact and the projectile was submerged within it. A less-intense reaction, found at a 7-inch air gap, was associated with debris moving backwards through the center of the incoming bubble material, as sketched in Figure 5. In this case, the debris bubble was fragmented prior to impact and the projectile was clearly visible, traveling ahead of the debris. Crater debris associated with impacts of particulate matter appeared to be responsible for this particular reaction pattern.

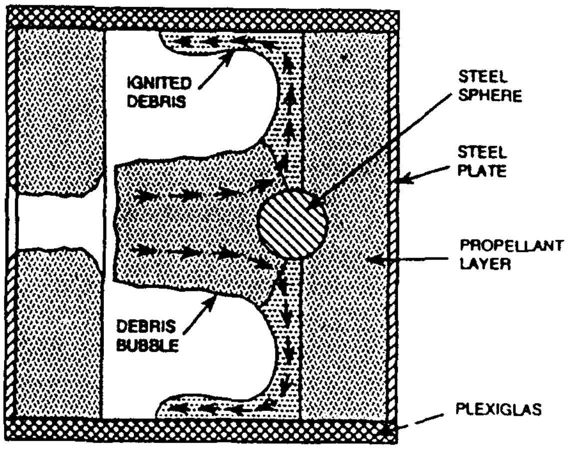

Fig. 4. Sketch of Propellant Flow/Reaction Patterns.

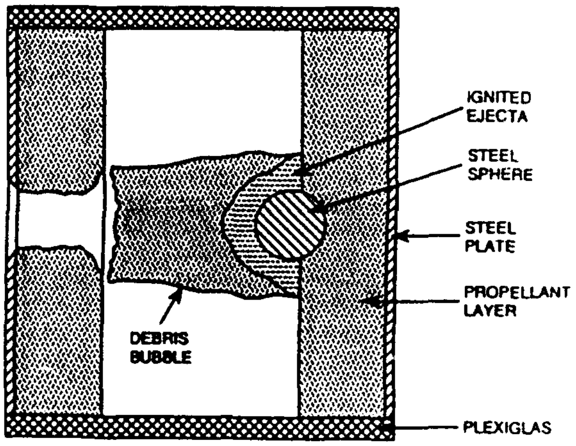

Fig. 5. Sketch of Crater Ejecta Reaction Pattern.

Both reactions appeared to take place largely in post-impact bubble debris. (This was determined by tests in which inert simulant was substituted for either the first or second propellant layer, Ref 2). There was little evidence of reaction involving pre-impact debris. Differences in reaction patterns were attributed to differences in bubble characteristics prior to impact; i.e., whether the bubble was unbroken or broken.

Estimates of burning reaction intensity were also made from the test film. Frame-to frame light intensity measurements were made using a hand-held exposure meter and then integrated to get an overall measure of reaction. Cover plate velocities were also measured to provide an estimate of internal pressurization. A plot of these two reaction measures against air gap width for propellant impacted at a constant impact velocity is shown in Fig. 6. The estimated distance for bubble breakup is also shown. Both measures show that maximum reaction occurs at an air gap where the bubble is unbroken prior to impact. Measurements for other propellant show similar results.

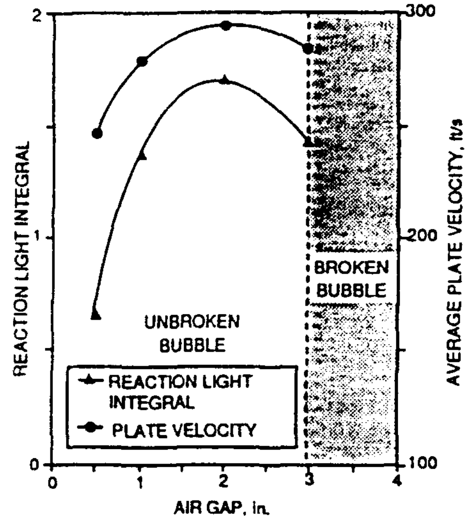

Fig. 6. Reaction Light Integral and Plate Velocity Comparison.

4.4.3 <u>Delayed Detonation</u>. For two minimum-smoke propellants and Composition B explosive, impact of the debris bubble on the second propellant layer resulted in delayed detonation within a certain range of air gaps. Detonation initiated at the point of impact (and usually within a few microseconds suggesting that confinement effects were not important in this situation) and propagated backwards through the wall of the bubble towards the first propellant layer, as shown in Fig. 7. The first layer usually detonated ahead of the second layer. (The latter appeared to detonate sympathetically with the first.)

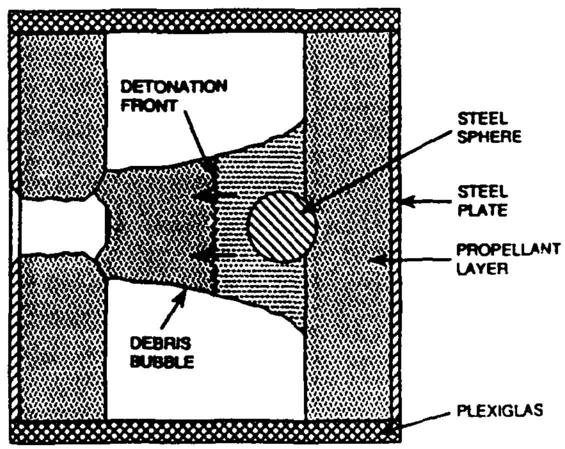

Fig. 7. Sketch of Delayed Detonation Process.

A plot of detonation delay time versus air gap for one propellant is shown in Fig. 8. (These values represent upper limit estimates because of the large interframe times.) The increased delay time for the largest air gap (2.75 inches) was believed caused by the onset of breakup along the front of the bubble. The increase for gaps less than 1.5 inches appeared to be due to a second detonation mechanism involving the second propellant layer and possibly confinement effects. (This conclusion was based on two tests, at 1.0 and 1.5 inch air gaps, in which inert simulant was substituted for the second propellant layer and where detonation occurred only at the larger air gap.)

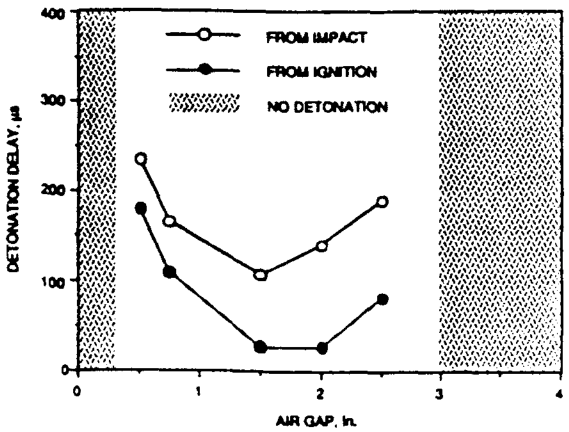

Fig. 8. Detonation Delay Times for a Minimum-Smoke Propellant.

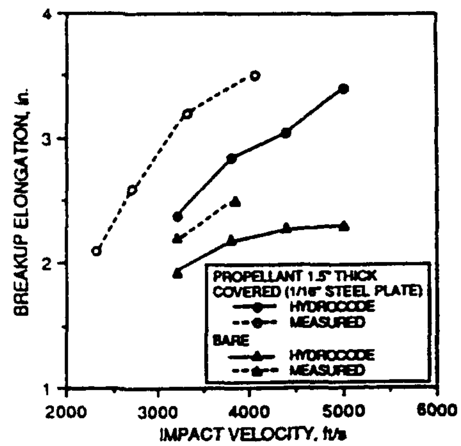

Fig. 10. A Comparison of Measured and Hydrocode-Calculated Bubble Breakup Elongations Versus Impact Velocity for a Minimum Smoke Propellant.

To examine the relationship between bubble breakup elongation and the upper detonation limit (i.e., the average between the largest air gap for detonation and smallest for burning), measured breakup elongations and detonation limits were compared with hydrocode-calculated breakup elongations. A comparison of breakup elongations for covered propellant as a function of propellant layer thickness is shown in Fig. 9. Agreement is quite good. A comparison of breakup elongations for both covered and bare propellant as a function of impact velocity is shown in Fig. 10. Measured values for this propellant are somewhat higher and differences between bare and covered material larger than predicted. Data trends for both target conditions are about the same as predicted ones, however. Measured breakup elongations probably represent upper bounds to the actual breakup elongations because of difficulties in determining the onset of breakup photographically.

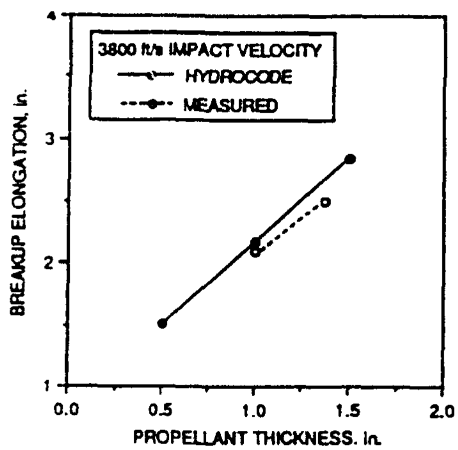

Fig. 9. A Comparison of Measured and Hydrocode-Calculated Bubble Breakup Elongations Versus Propellant Layer Thickness for a Minimum Smoke Propellant.

A comparison of measured detonation limits and hydrocode-calculated breakup elongations for both covered and bare propellant as a function of impact velocity is shown in Fig. 11. Detonation limits for bare propellant appears to be relatively constant over this velocity range indicating that the breakup elongation remains roughly the same. This behavior is quite different than that for covered propellant where the breakup elongation increases with impact velocity. These differences may be attributed to differences in projectile deform ion for the two impact conditions. Projectile deformation is relatively small for impact against bare propellant at these velocities resulting in a more constant bubble size. In contrast, projectile deformation becomes significant at the higher velocities for impacts against covered propellant resulting in a larger bubble.

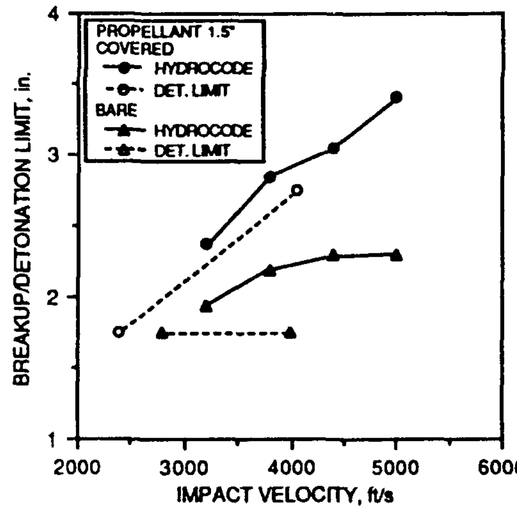

Fig. 11. A Comparison of Measured Detonation Limits With Hydrocode-Calculated Bubble Breakup Elongations Versus Impact Velocity for a Minimum Smoke Propellant.

The effect of propellant brittleness on the detonation limit was examined using Composition B explosive. For impact of spheres at 3800 ft/s, the measured detonation limit for covered Composition B was 1.50 inches as compared to 2.75 inches for propellant. This reduction is consistent with the smaller breakup elongation expected for a brittle material (Ref 5).

The effect of projectile geometry on the detonation limit was examined using ogival-fronted cylinders. At an impact velocity of 3800 ft/s, the measured detonation limit for ogival projectiles against bare propellant was 1.25 inches as compared to 1.75 inches for spheres. This reduction reflects the lower penetration resistance for this nose shape that allows easier perforation of the bubble wall.

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Discussion

QUESTION BY VICTOR, US: Based on the timing and the similarity of the phenomena it would appear that what you see in the planer tests you reported on and what Brunet reported on in the cylindrical tests there seems to be similar phenomena that are explained by different reasonable explanations. Have you any comment on this?

ANSWER: Yes, it is fundamentally the same mechanism in that both require damage to the propellant do to tension in the bubble or coalescence with the shock wave followed by a compression shock which then detonates the system.

The effect of heating rate in Cook-off testing of energetic materials

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SUMMARY

A thorough understanding of the chain of events that occur within an ordnance when it is subjected to a thermal stimulus is needed to describe the cook-off occurrence. It was proposed that these mechanisms should consider i)the system configuration, ii) materials and iii) the type of thermal environment that poses a viable threat to the energetic material. The attempts to satisfy these requirements at DREV has led to a cook-off test that simulates variable thermal environments on a system configuration that best addresses our needs. The energetic material to be tested with these tests includes all PBX's in development at DREV.

This paper aims to present the methodology of the cook-off test at DREV, using guidelines from U.S. DOD-STD-2105(NAVY) (3.3°C/h) and three other intermediate heating rates to show the effect of heating rate on the reaction temperature of explosives. The ordnance is defined by a representative design of a 150mm ordnance system with predefined constants of size and confinement. The energetic material chosen for these tests was DREV's CX-84A.

List of Symbols

c	heat capacity
E	activation energy of the reaction
k_o	pre-exponential factor
Q	reaction heat
$\dot{q}$	heating rate
R	gas constant
t	time to reaction
T_i	initial temperature
T	reaction temperature

1. INTRODUCTION

The cook-off occurrence of an explosive is described as an unintended reaction of the energetic material due to a varying thermal environment. The thermal environment may consist of the munition's exposure in a fire to the munition's cyclic thermal loading while being transported or being stored. The thermal decomposition of the munition depends on the heat exchange with the surroundings. Of particular danger, and of special interest to many researchers, is the slow cook-off process. The cook-off phenomena occurring at slow heat rates or lower temperatures depends on the mass of the explosive, the exposed surface of the material, the applied heat rates, etc. The reaction temperature of the explosive at low ambient conditions is usually less than that experienced at high heat environments. The thermal decomposition of the explosive proceeds slowly at low ambient conditions and the heat transfer is efficient since most of the heat generated in the environment is transferred to the explosive. Whereas, for higher heating environments such as a fast cook-off, the generated heat is dissipated and the heat transfer is less efficient. In simulating realistic situations or stimuli, the munition may be exposed to a cook-off mechanism which can be a combination of both or an intermediate other than the slow or fast cook-off. An example of this may be the heat transfer from a hot gun barrel to a lodged muniton casing. The complexity of the cook-off mechanism is also dependant on the degree of confinement and the mass of the explosive. The ideal scenario would include munitions of practical size and confinement subjected to a hazardous thermal environment. In this study, an experimental method, with known explosive mass contained in a generic munition casing, has been developed in order to determine a relationship between the heating rate and the reaction temperature of an explosive when subjected to various heating rates.

2. METHOD

For each experiment, a metal cylinder filled with energetic material was subjected to a controlled thermal environment via an enclosed oven. A schematic of the cylinder is shown in Figure 1a and a generic schematic of the test is shown in Figure 1b. The design consideration for the cylinder was to simulate as realistically as possible a 155 mm warhead containing 5 Kg of explosive. The cylinder's volume was 3L and the top cover (Cover B) was specifically designed to burst at an internal pressure between 22MPa-24MPa, which simulates the munition's bursting pressure. The placement of the container within the oven was carefully considered in order to minimize varying heat flux and large air temperature gradients. The heat flow on all surfaces of the container were to depict a free flowing convective and

conductive heat transfer.

As the oven was heated, four temperature measurements were obtained by type K (chromel/alumel) thermocouples. One thermocouple measured the temperature of the explosive/metal interface at the longitudinal center of the container. Another was placed within the oven at the mid point of the air gap between the heating elements and the explosive container in order to log the oven temperature. This thermocouple was situated along the plane perpendicular to the mid point of the longitudinal axis of the cylinder. The third and fourth thermocouple charted the temperature of the air gap at both the top and bottom edge of the cylinder. These two thermocouples gave the temperature gradient of the air along the length of the cylinder. Each thermocouple was attached to a two wire transmitter (ACROMAG 150[illegible]). The transmitters were used to condition thermocouple input signals and convert the signal to a 4 to 20mA process current output. The units were calibrated for a 0° to 700° C input for the 4 to 20 mA output range. A 24Vdc power supply with a 500Ω series resistant was attached to each of the transmitters.

A data acquisition system (HP3852a) was used to obtain the measurements of the thermocouples. Modules for the system in the form of a voltmeter and a 20 channel relay multiplexer were needed for the data acquisition configuration. This permitted the output voltage from the thermocouples to be converted to actual temperature readings by incorporating a relation within the computer program.

Using programmable PID control via a micro computer, the heating environment could be varied at any stage of the experiment. A computer programs the functions and downloads into the data acquisition/control unit, with which the latter controls a closed 3 KW oven with a feedback transfer function interpreted by the temperature reading obtained by the center thermocouple located in the oven.Cylindrical brick refractory type ovens rated at 3 kW were used for the experiments. A silicon relay with a 0 to 5 Vdc setting was used concurrently with an analog/digital converter,via feedback from the oven thermocouple reading, to control the 240Vac power supply to the oven. An isolation transformer was placed in the voltage line to protect the equipment in case of a short circuit or power surge when a reaction occurred within the oven.

A video camera was also used to record the event of the reaction of the explosive. It was placed in a well protected environment and the image of the oven was transmitted to the camera via mirrors. A pressure transducer (Kistler Model 206) placed at 5m from the oven was also used to record the pressure wave (blast) of the reaction.

DREV CX-84A explosive was cast into four cylinders and each cylinder was subjected to one of the predetermined heating rates. After filling, the explosive cylinders were stored at an ambient temperature of 20°C until the cook-off test was initiated. The applicable heating rates for the cook-off test were 3.3°C/h, 9°C/h, 25°C/h and 75°C/h. Thermocouple readings were obtained for each test until a reaction was recorded within the cylinder. The time for the cook-off was also recorded.

During each test, the oven was heated to approximately 100°C using higher heating rates than the applicable rates in order to accelerate the cook-off process. This conditioning has no adverse affect on the explosive's reaction because the temperature is more than 50°C lower than the assumed exothermic reaction temperature of the explosive. The heating rate was then kept constant at one of the four mentionned heating rates for the duration of the test.

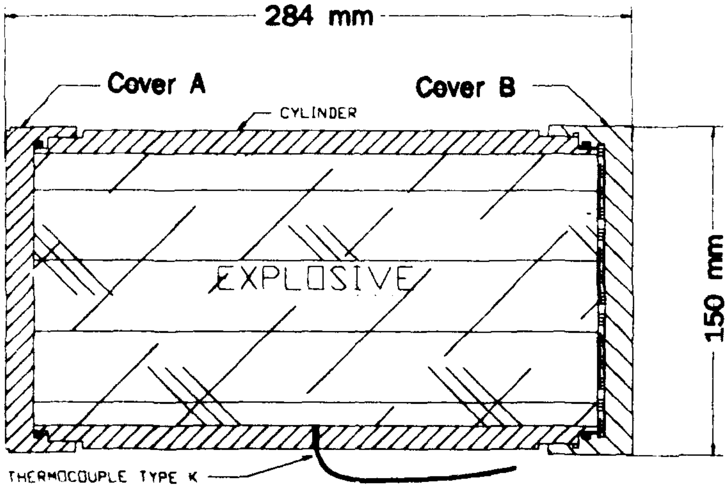

Figure 1a: Explosive filled cylinder

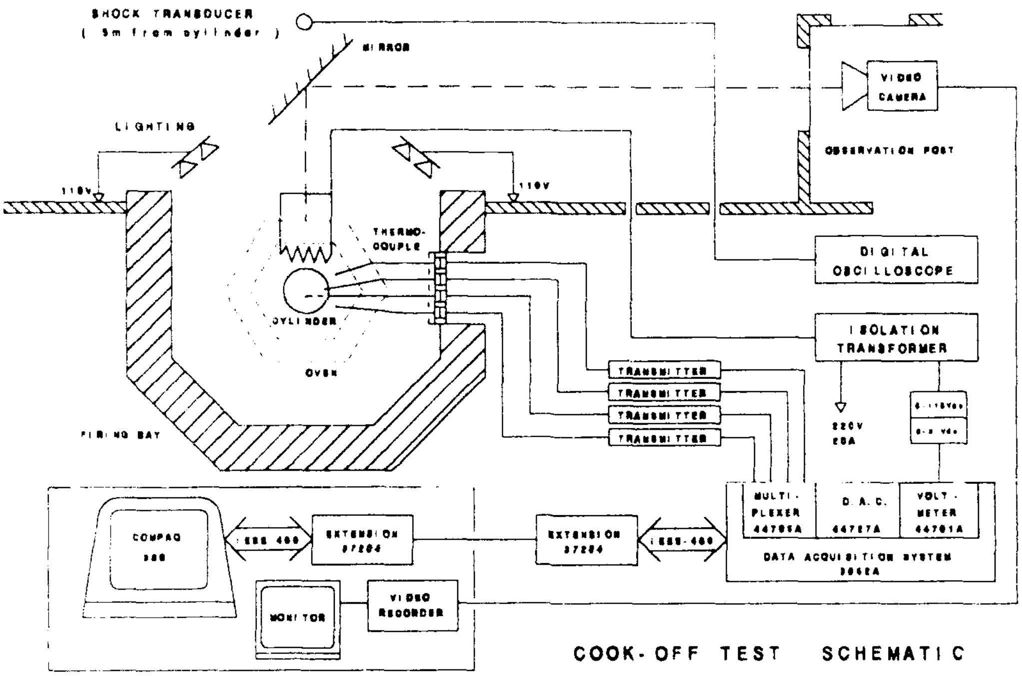

Figure 1b: Schematic of cook-off setup

3.RESULTS AND DISCUSSION

Figures 2 to 5 show an array of results showing the oven temperature and the temperature of the explosive/cylinder interface within the cylinder at the four heating rates. The graphs also display the time to reaction. It is first noticed that the time to cook-off was greater at low heating rates. At a heating rate of 3.3°C/h, the time for a reaction to occur, as measured from the reference oven temperature of 100°C was 21.4 hours, whereas, at a heating rate of 75°C/h, the time was only 2.5 hours. The time for reaction at 9°C/h and 25°C/h was 9.8 and 4.9 hours, respectively. The reaction temperature has also changed. The reaction temperature increased from 153°C as measured at 3.3°C/h to 179°C as measured for the heating rate of 75°C/h. The reaction temperatures at 9°C/h and at 25°C/h were found to be 165°C and 172°C, respectively. The phenomena of increased reaction temperature concurs with analytical work treating the effect of low and high temperatures [Ref.1,2,3,4]. However, the analytical work only estimates the relative increase, since not enough practical data has been collected to accurately predict the explosives behaviour in any confinement at various heating rates. However, there is ongoing work by many countries to model the reaction of energetic materials, in various states of confinement, to various thermal environments using experimental data.

Figure 6 illustrates the correlation of the reaction temperature to that of the heating rate of the oven. It has been found that the experimental data can be fitted to an equation of the form of the approximated expression derived by Frank-Kamenetsky [Ref.5] which approximates the growth of the reactant temperature of a large body. The expression assumes adiabatic conditions and that the heat loss rate is small compared to the growing rate of heat generation. The expression is of the form

$$T = T_i + \frac{RT_i^2}{E} \cdot \ln \frac{1}{1 - \frac{Q}{c} \cdot \frac{E}{RT_i^2} k_o (e^{E/RT_i}) t} \qquad (1)$$

which describes the convective heat transfer across the body and does not include the relation for the shape factor function for the conductive heat transfer. Frank-Kamenetsky proposed a function Fk, to be included within the equation, to simulate the conductive heat transfer thoughout the reactant. The variables characterized in Fk were the material's thermal conductivity, density and shape factor. The relationship, however, does not consider the effects of confinement of the energetic material, the convective heat

transfer through various materials other than the energetic material and also the conductive properties through the metal encasement. Such consideration would require a complex model. Therefore, the best fit relation of the experimental data to the model, in simplified constants or terms, was found to be

$$T=144.97+8.156\cdot\ln(\dot{q}) \tag{2}$$

Equation (2) is unique in that it is the expression obtained for the reactant temperature of the explosive CX-84A, confined in a metal cylinder, as a function of the heating rate.

The intensity of the reaction at each heating rate was also noted for each cylinder and they were found to be similar, as indicated by the bursting mechanism of the cylinder and as shown in the photographs in Figures 7 and 8. For each case, the cylinder top which was rated for 24 MPa, burst open at the weakened seam and the energetic material was extruded out of the cylinder. The extruded explosive along with its remains within the cylinder burned until it was totally consumed. The degree of reaction at all cases was minimum as evidenced also by the negligible pressure wave measured by the pressure transducer at the time of reaction. The pressure wave at 5 m from the cylinder was measured at less than 6 kPa.

The results indicate that the explosive does not react violently for various cook-off scenarios and that the reaction temperature is dependent on the cook-off parameter of heating rate.

4. Conclusion

The cook off method adopted at DREV adds versatility to the existing cook-off method described in DOD-STD-2105A by altering the thermal environment of the test sample. The method attempts to depict thermal environments that simulate tangible hazardous thermal scenarios of munitions of any size and confinement. The procedure can realize tests at various heating rates and has shown experimentally that the energetic material's reaction temperature is a function of the thermal environment. DREV explosive CX-84A has been tested in a generic 155 mm casing and its reaction temperature was found to be a function of the heating rate applied. This relation is unique for the size and confinement of the explosive.

The reaction state of CX-84A to these different thermal environments was also found to be minimal as confirmed by its burning reaction and there was no significant evidence that the heating rate affected the degree of reaction. The degree of reaction of CX-84A, at the slow cook-off rate of 3.3°C/h, has shown that the explosive has passed the insensitive DOD-STD-2105A requirements for the test (i.e. reacted above 149°C and reaction was a burn [Ref 6]).

5. References

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3. Merzhanov A.G., Abramov V.G., "Thermal Explosion of Explosives and Propellants", Propellants and Explosives, 6, 1981, pp 130-148.

4. Merzhanov A.G., Averson A.E., "The Present State of the Thermal Ignition Theory: An Invited Review", Combustion and Flame, 16, 1971, pp 89-124.

5. Frank-Kamenetsky D.A., "Diffusion and Heat Exchange in Reaction Kinetics", Princeton University Press, Princeton, New Jersey, 1955.

6. DOD Military Standard,"Hazard Assessment Tests For Non-Nuclear Munitions", MIL-STD-2105A (Navy), DRAFT, January 19,1990.

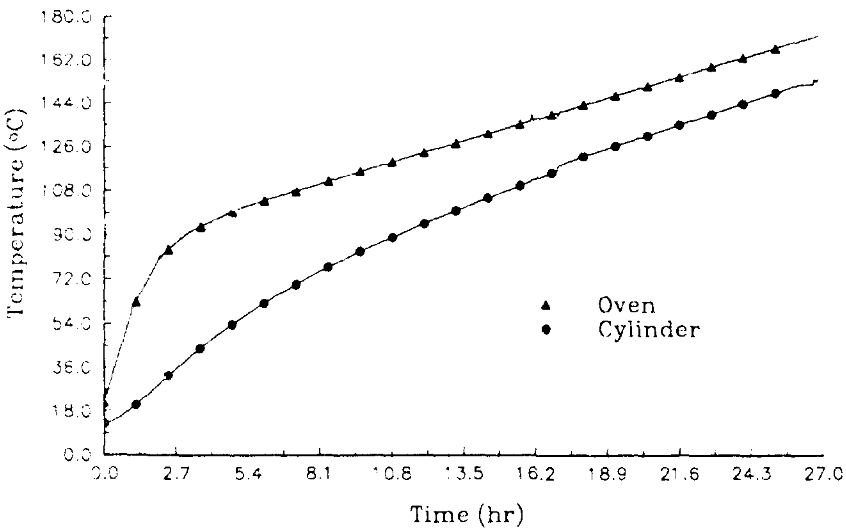

Figure 2: Results at 3.3oC/h.

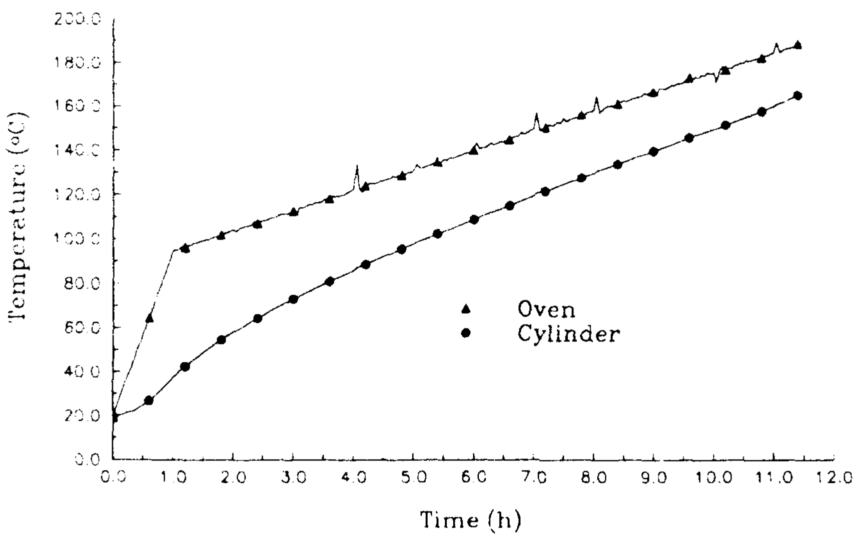

Figure 3: Results at 9oC/h.

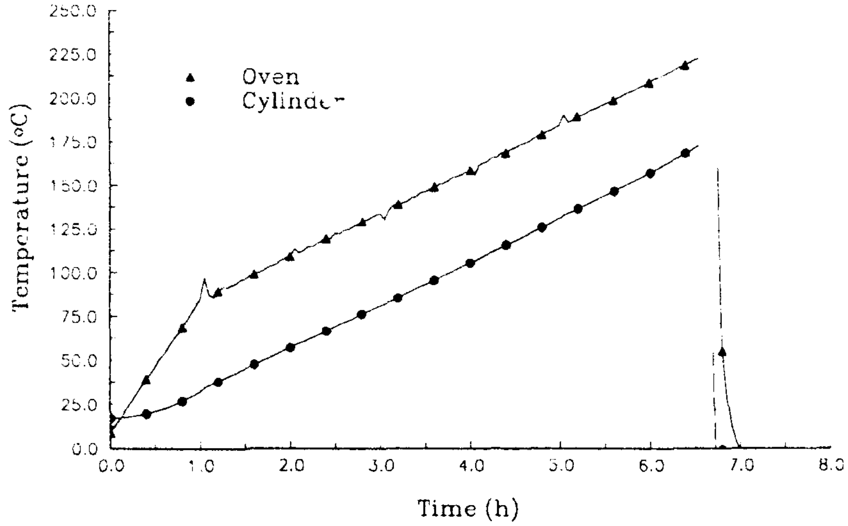

Figure 4: Results at 25°C/h.

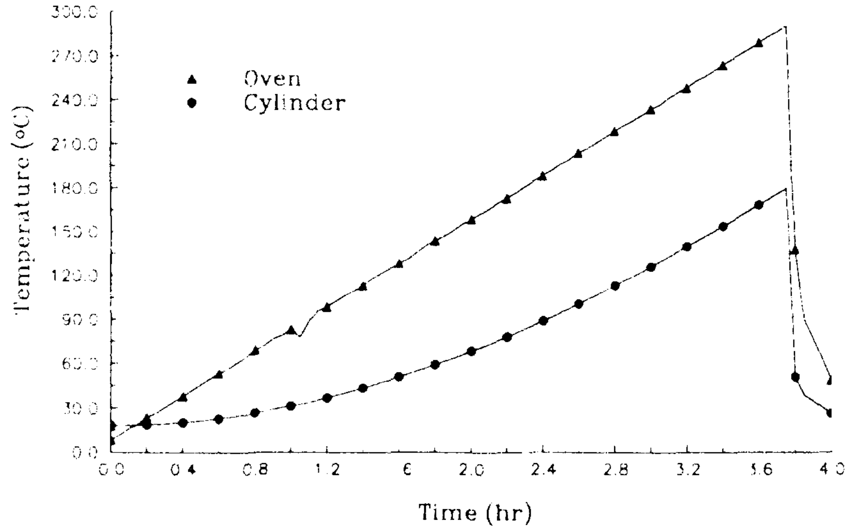

Figure 5: Results at 75°C/h.

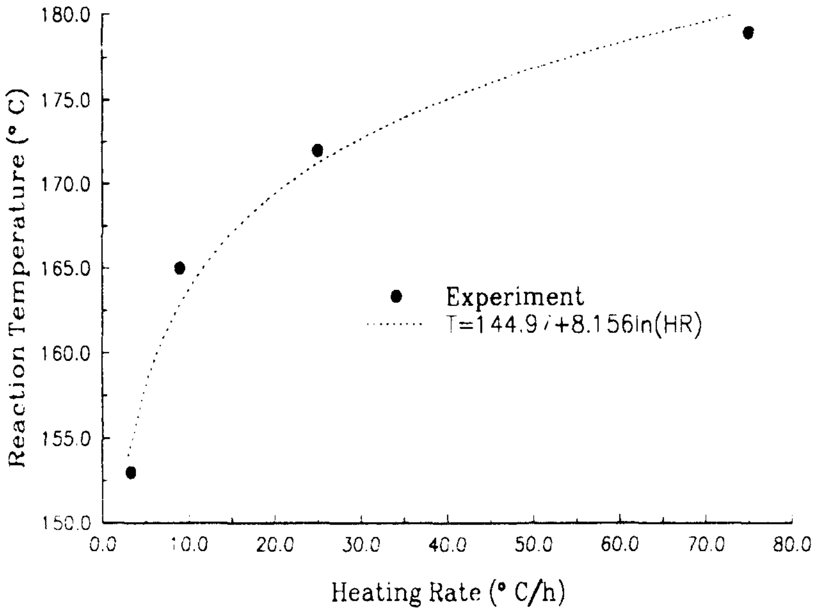

Figure 6: Correlation of the experimental data.

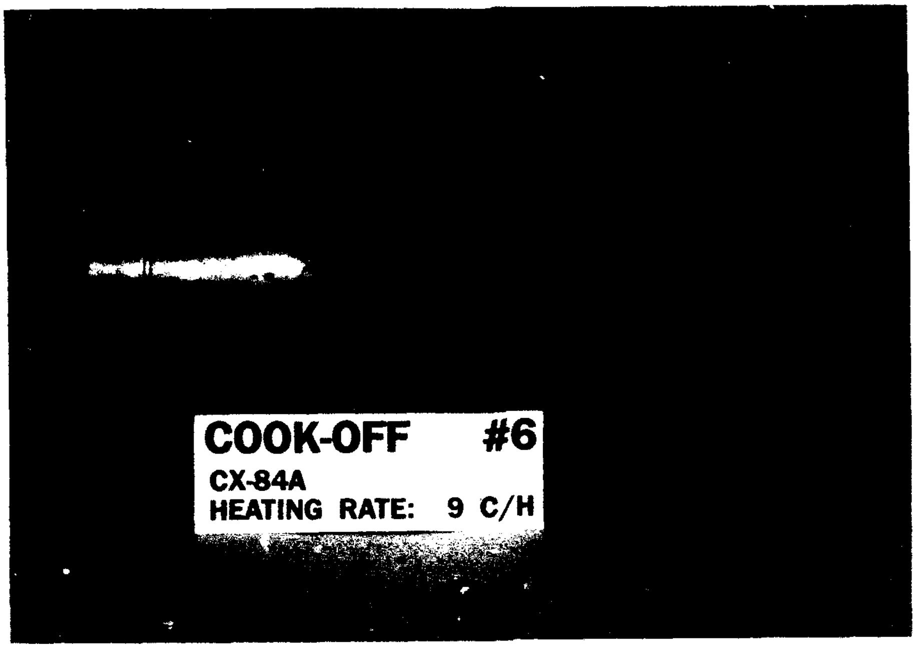

Figure 7: Photograph of cook-off cylinder after test at 9°C/h.

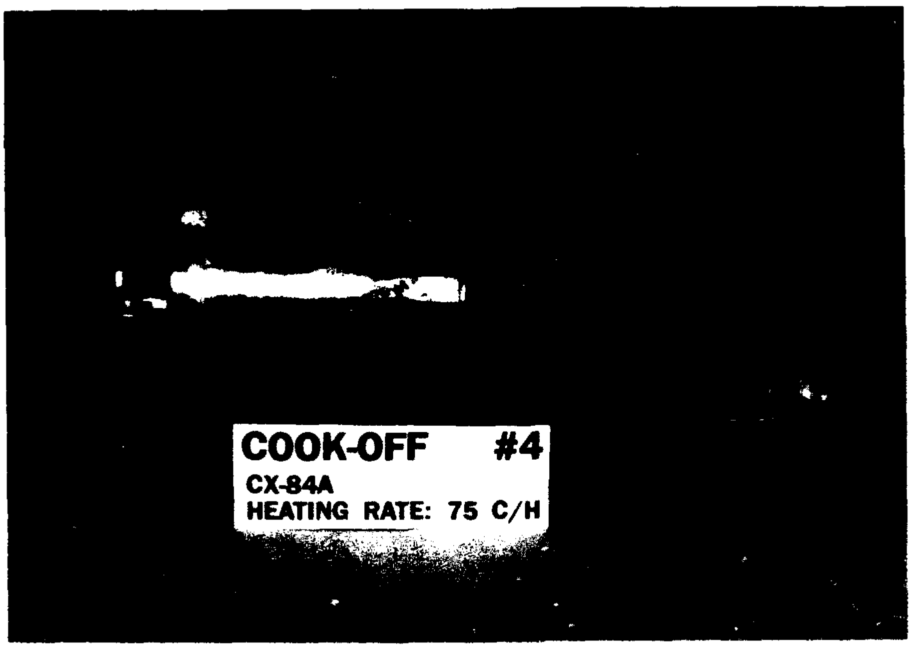

Figure 8: Photograph of cook-off cylinder after test at 75°/h.

Discussion

QUESTION BY SCHARP, ?: You did not put a thermocouple in the center of the explosive. Did you make theoretical calculations on the expected heat transfer and temperature in the explosive?

ANSWER: No, I have not made theoretical calculations but they are forthcoming.

QUESTION BY VAN DER STEEN, THE NETHERLANDS: The heating rate for a cook off experiment is 3.3 degrees C/hr. This causes a very lengthy experiment. Could we conclude from your experiment that a higher heating rate, eg 25 degrees C/hr., is also possible for a "slow cook-off test"?

ANSWER: Not exactly, the correlation curve for each system configuration must include testing at 3.3 degrees C/hr. in order for proper extrapolation.

PHENOMENES THERMIQUES INDUITS PAR UN ACCIDENT DE MUNITION A BORD D'UN NAVIRE

THERMAL PHENOMENA INDUCED BY AN AMMUNITION ACCIDENT ON BOARD SHIPS

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RESUME

Après avoir passé en revue les principaux risques liés aux phénomènes thermiques induits à bord des bâtiments de surface par la mise à feu accidentelle de munitions, on présente les travaux expérimentaux et théoriques menés au G.E.R.Py dans le domaine des agressions thermiques :

- effets globaux produits par un foyer localisé dans une soute , transferts thermiques vers les locaux adjacents et comportement des munitions vis à vis de ces agressions,

- effets locaux produits en particulier par les jets de propulseurs sur les structures environnantes en cas d'allumage intempestif.

INTRODUCTION

L'objet de cet exposé est de présenter les travaux expérimentaux et théoriques menés dans le domaine des agressions thermiques à bord des bâtiments de surface par le Groupe d'Etudes et de Recherche de Pyrotechnie (G.E.R.Py) de la Direction des Constructions Navales de Toulon.

Les nombreux incidents survenus à bord de bâtiments de surface et notamment celui survenu en mai 1987 sur l'USS STARK ont mis en évidence les risques liés aux phénomènes thermiques (foyers d'incendie, transferts de chaleur) et en particulier ceux induits par la combustion de matières actives (propergol).

Tout peut commencer par un foyer d'incendie localisé par exemple dans une soute provoquant une élévation de température et de pression dans le local jusqu'à réaction d'une ou plusieurs munitions soumises à cette ambiance thermique.

Au niveau de la **munition**, les risques peuvent être classés selon le type de réaction, à savoir :

- **réaction de détonation** (type I ou II selon le projet de STANAG 4240) avec endommagement des structures environnantes par la surpression due à l'effet de souffle et par les perforations provoquées par les éclats (fragmentation de l'enveloppe). Les travaux récents sur les explosifs permettent de se garantir contre ce risque.

- **réaction d'explosion** (type III) avec fragmentation de l'enveloppe, projection d'éclats et effets locaux de surpression,

- **réaction de propulsion** (type IV) avec départ intempestif de la munition engendrant des dégâts importants sur les structures et l'apparition de foyers d'incendie dits secondaires,

- **réaction de combustion** (type V) sans propulsion ni ouverture violente de l'enveloppe, avec création de foyers d'incendie localisés.

Au niveau des **aménagements**, on distingue :

- les effets globaux caractérisés par des gradients de température, de pression ou de vitesse d'écoulement des gaz brûlés dans les locaux de stockage ou de mise en oeuvre (soutes) et dans les conduits d'évacuation (plénums). Ces élévations de température peuvent provenir des foyers directement placés dans le local ou de foyers situés dans des locaux voisins (échauffement lent),

- les effets locaux dont les effets des jets (pression et température à l'impact, vitesse d'écoulement des gaz) sur les structures et munitions voisines. Ces jets peuvent être générés par le départ intempestif de propulseurs ou issus de perforations par éclats de ces mêmes propulseurs.

Les travaux traités par le G.E.R.Py concernent la caractérisation de ces effets globaux, l'étude du comportement des munitions et des effets locaux ainsi que les protections associées. On présente successivement les travaux expérimentaux, puis les travaux théoriques.

TRAVAUX EXPERIMENTAUX

Trois types principaux d'essais sont effectués au G.E.R.Py :

- en premier lieu, des **essais d'incendie à l'air libre** permettant de mieux connaître l'agression elle-même. Il s'agit de faire brûler différents combustibles (hydrocarbures, propergols, explosifs) et de mesurer la distribution spatiale et temporelle des températures et des flux rayonnés par le foyer.

Description du moyen d'essai à l'air libre

Le combustible est disposé dans un bac de sable, tapissé d'une feuille de polyéthylène, de dimensions 6 m x 6 m ou dans un bac métallique de dimensions 1.5 m x 1.5 m. Les combustibles testés sont des hydrocarbures ou des matières actives (propergol ou explosif). La mise à feu s'effectue par allumage pyrotechnique (hydrocarbures) ou fil résistant (matières actives). Les mesures effectuées sont de deux types : température (thermocouples chromel-alumel) et flux (fluxmètre de rayonnement). Une caméra vidéo permet de suivre le déroulement de l'essai. Une ou plusieurs caméra rapides (quelques centaines à quelques milliers d'images par seconde) permettent de visualiser des instants caractéristiques de l'incendie. La durée de l'incendie varie de 1 à 15 minutes.

L'annexe A-1 présente une courbe de température et une courbe de flux en fonction du temps obtenues lors d'un essai de combustion d'hydrocarbure.

Pour une température moyenne du foyer de 1300 K, on mesure un flux de rayonnement de 2.3 kW/m^2 à 16 m.

- en second lieu, des **essais d'incendie en milieu semi-confiné** permettant d'acquérir des données sur l'ambiance régnant dans une soute et dans les plénums soumis à un incendie et d'apprécier les transferts thermiques vers les locaux adjacents. Ces essais sont effectués dans une enceinte fermée avec un foyer suffisamment réduit ou dans une enceinte munie d'un conduit d'évacuation de sorte que la pression moyenne n'augmente pas de plus de quelques centaines de millibars.

Description du moyen d'essai en milieu semi-confiné

On dispose de trois enceintes parallélépipédiques de dimensions 1m x 1m x 2m. La première où est situé le foyer d'incendie est appelée "volume émetteur". Les deux autres enceintes placées respectivement à côté et au-dessus du "volume émetteur" sont appelées "volumes récepteurs". Ce dispositif est aussi utilisé pour l'évaluation de l'efficacité des protections thermiques. Les mesures effectuées dans le "volume émetteur" concernent la pression (par capteur), la température (par thermocouple), la vitesse des gaz (par fil chaud), la masse de combustible brûlé (par pesée continue), le débit de gaz évacué par le conduit (par débitmètre) et les flux thermiques à travers les parois (par fluxmètre). Dans les "volumes récepteurs", on mesure la température et la pression.

Des essais sont actuellements conduits avec différents combustibles (propergol et explosif).

- en dernier lieu, des **essais d'impact de jets** de propulseur sur une plaque instrumentée et recouverte de matériaux caractéristiques (par exemple des protections thermiques) permettant de visualiser la structure du jet, de mesurer les pressions, les températures (thermocouples haute température tungstène-rhénium) et les flux thermiques à l'impact et d'évaluer la tenue des matériaux testés.

Description du moyen d'essai d'impact de jets

Pour ces essais, on place le propulseur (ou le générateur de jet) sur une potence de hauteur réglable (de 0.5 m à 2 m), le jet étant dirigé vers le bas sur une plaque circulaire de rayon 0.5 m. On visualise le jet à l'aide de caméras rapides et on mesure les pressions, les températures, les flux thermiques et la poussée globale (par capteurs de force) sur la plaque.

On présente un enregistrement de température sur une plaque recevant un jet de débit massique de 1 kg/s pendant 0.5 s et située à 1.5 m. Une température maximale de 1213 K est mesurée à 0.2 m de l'axe du jet (annexe A-2).

Tous ces résultats expérimentaux sont utilisés comme données d'entrée ou comme valeurs de recalage des différents codes de calcul utilisés lors de la modélisation de ces phénomènes.

TRAVAUX THEORIQUES

Les travaux de modélisation des conséquences d'une agression thermique sont menés au G.E.R.Py avec les outils numériques suivants :

- **ANSWER** : code de mécanique des fluides tridimensionnel aux Volumes Finis développé par ACRI (USA) et PRINCIPIA (France) utilisé pour les calculs d'incendie en milieu semi-confiné (champs de pression, de température et de vitesse des gaz dans une soute ou un conduit) et

pour les calculs d'impact de jets (température, pression, vitesse).

Ecoulement dans un milieu semi-confiné

On étudie les conséquences de l'allumage intempestif d'un propulseur placé dans une soute à laquelle est raccordé un plénum.

Le calcul effectué en configuration axisymétrique utilise comme conditions initiales la pression atmosphérique et une température de 290 K, comme conditions génératrices de l'écoulement une pression de 10 MPa et de 2800 K, ce qui entraîne comme conditions de sortie de jet une pression de 1 MPa , une température de 1500 K et une vitesse de 2000 m/s.

Etude du jet à la sortie de la tuyère

La soute a un rayon de 0.7 m et une longueur de 1 m. Le pas de temps est de 10^{-6} s. Les résultats présentés concernent la pression puis la température à 1 ms (annexe A-3).

Etude du jet dans l'ensemble soute-plénum

La soute a un rayon de 1 m et une longueur de 3 m. Le plénum a un rayon de 0.3 m et une longueur de 9 m.

On présente la pression et la température à 250 ms puis à 500 ms ainsi que l'état stationnaire (annexes A-4 & A-5).

A 250 ms, l'écoulement est bloqué. Le jet est alors refoulé dans la soute entraînant une élévation de la pression et de manière plus significative de la température.

- **ABAQUS** : code thermo-mécanique tridimensionnel aux Eléments Finis developpé par H.K.S. (U.S.A.), utilisé pour les calculs de réponses d'une munition ou d'une structure à une agression thermique (température et flux) ainsi que pour les évaluations des temps de réaction.

On présente les résultats en température d'une munition soumise à un incendie de température 900 K.

Au bout de 6 mn, ce qui correspond au temps de réaction de la munition, on obtient 650 K sur l'enveloppe extérieure et 490 K dans l'explosif (annexe A-6).

- **NSTC3D et ESTET** : développés respectivement par l' I.N.R.I.A. et l' E.D.F. (France) utilisés pour les calculs d'incendie en milieu confiné (champs de pression, de température et de vitesse).

- **NSTC3D** : code de mécanique des fluides tridimensionnel compressible aux Eléments Finis pour la modélisation d'un feu de combustible et des transferts thermiques aux parois du "volume émetteur".

Les conditions initiales à l' intérieur du local sont la pression atmosphérique, une température de 290 K et une vitesse d'écoulement nulle.

L'écoulement gazeux est supposé compressible, laminaire, le gaz parfait et transparent, la viscosité constante.

Le foyer est modélisé comme une source de propergol solide surfacique de dimensions 0.5 m x 1 m, de température 2800 K et de débit massique 0.5 kg/s pendant 10 s.

On prend une condition limite de convection avec un coefficient de 10 $W/m^2.K$ sur la paroi mitoyenne, les autres parois étant supposées adiabatiques.

Les résultats en température de peau du volume émetteur montrent que la température moyenne au centre de la paroi séparatrice est de 2500 K (annexe A-7).

- **ESTET** : code de mécanique des fluides tridimensionnel aux Différences Finies et aux Volumes Finis pour la modélisation des transferts thermiques et la mise en mouvement du fluide par convection naturelle dans les "volumes récepteurs".

Les conditions initiales du calcul (consécutif au précédent) sont identiques. Le fluide est supposé incompressible, dilatable et turbulent. La paroi opposé à la paroi mitoyenne (supposée à 1500 K) est à 290 K et les autres sont adiabatiques.

On présente les résultats en température et en vitesse au bout de 10 s de simulation. La température sur la paroi supérieure du volume récepteur est de 470 K (l'expérience donne 420 K). Le champ des vitesses met en évidence les phénomènes de convection (annexe A-8).

D'autres codes monodimensionnels développés au G.E.R.Py sont utilisés pour les prévisions et les études paramétriques :

- **MEGALO** : code de mécanique des fluides pour le calcul des valeurs moyennes (pression, température, vitesse) dans un volume correspondant à une soute ou à tout ou partie d'un plénum.

Le code a été validé par comparaison avec des essais à échelle réduite (1/7) et un essai en grandeur réelle. Les

surpressions calculées ont été correctement confirmées par les mesures.

DIMENSIONNEMENT D'UN PLENUM

Roquette débit 5 kg/s pendant 0.3 s
Soute de 33 m ^{3}

nombre de roquettes	Pression Absolue bar (Soute Fermée)	Pression Absolue bar (Soute Ouverte) 0.25 m ^{2}	0.81 m ^{2}
1	2.2		
3	4.5		
6	6.2		
15	9.2		
1		1.46	1.40
6		3.35	1.40
15		4.13	2.10

Les résultats d'une étude de dimensionnement d'un plenum présentés dans le tableau suivant :

- **FLAM2** : code aux Différences Finies pour le calcul des transferts thermiques par conduction à travers différentes couches de matériaux en tenant compte des réactions internes et des changements de phases.

Le recalage du programme a d'abord été effectué avec une munition (bombe) chargée en explosif "coulé-fondu" puis en explosif "composite" (octorane et hexabu). Les résultats sont consignés dans le tableau suivant :

Temps d'apparition de l'événement pyrotechnique (s)

Foyer 1.5 m * 1.5 m

	Hexabu	Octorane	Tolite
Calculs Température flamme K			
1150	154	189	140
1075	197	246	178
975	200	374	260
Essais	200	260	270

Le temps d'apparition de l'événement pyrotechnique calculé montre une très grande sensibilité à la température du foyer. Il importe donc lors de la réalisation des essais de caractériser avec précision cette température en multipliant les points de mesure. Compte-tenu de ces différences entre température réelle et température théorique (selon la norme spécifique du type d'incendie), on constate en général une assez bonne corrélation entre calcul et expérience avec ce type de code simplifié.

CONCLUSIONS

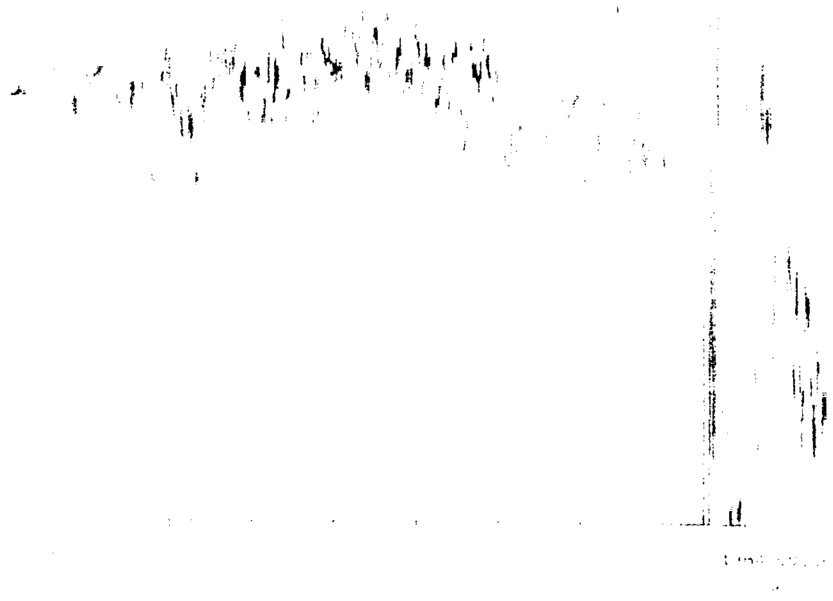
Les travaux conduits par le G.E.R.Py sur les plans expérimental et théorique permettent d'ores et déjà d'évaluer les conséquences d'une agression thermique à bord d'un navire. Toutefois la difficulté réside dans la multiplicité des scénarios d'accident possibles. Un effort de réflexion est à mener sur ce thème pour mieux adapter les outils de prévision.

On cherche aussi à mieux décrire la réponse de la munition en affinant la description des phénomènes physiques qui se produisent entre l'instant où la matière active est initiée et l'ouverture de l'enveloppe.

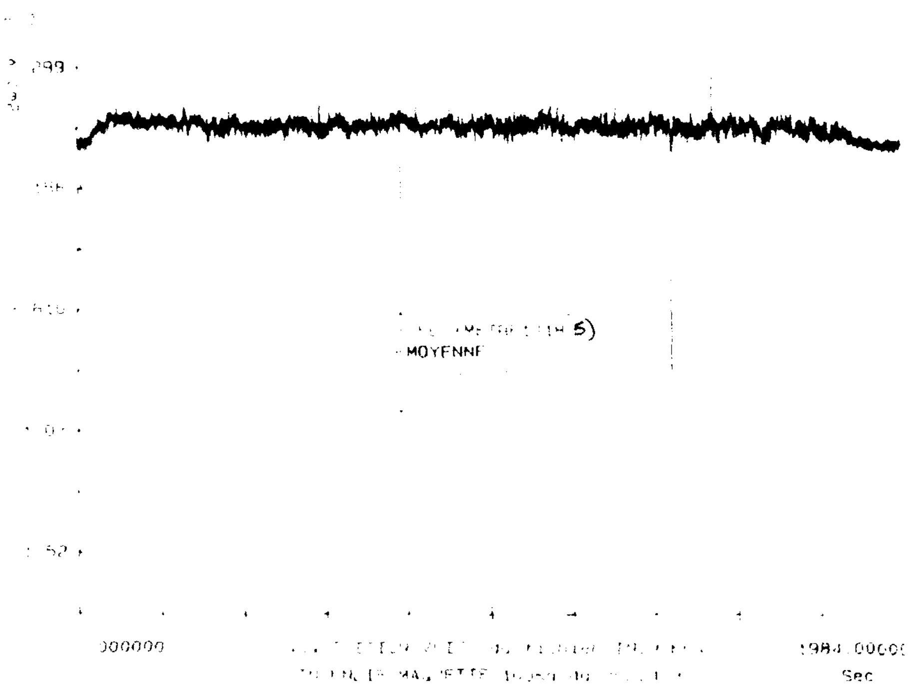
Enfin, il ne faut pas oublier les actions menées dans le cadre de la lutte contre les foyers d'incendie (par exemple arrosage) qui doivent être prises en compte dans les modèles.

ANNEXE A-1

COMBUSTION D'HYDROCARBURE



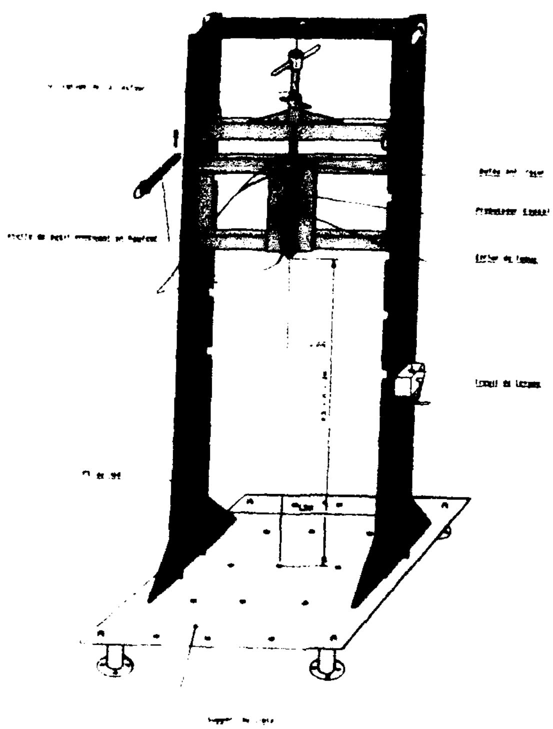
EVOLUTION DE LA TEMPERATURE



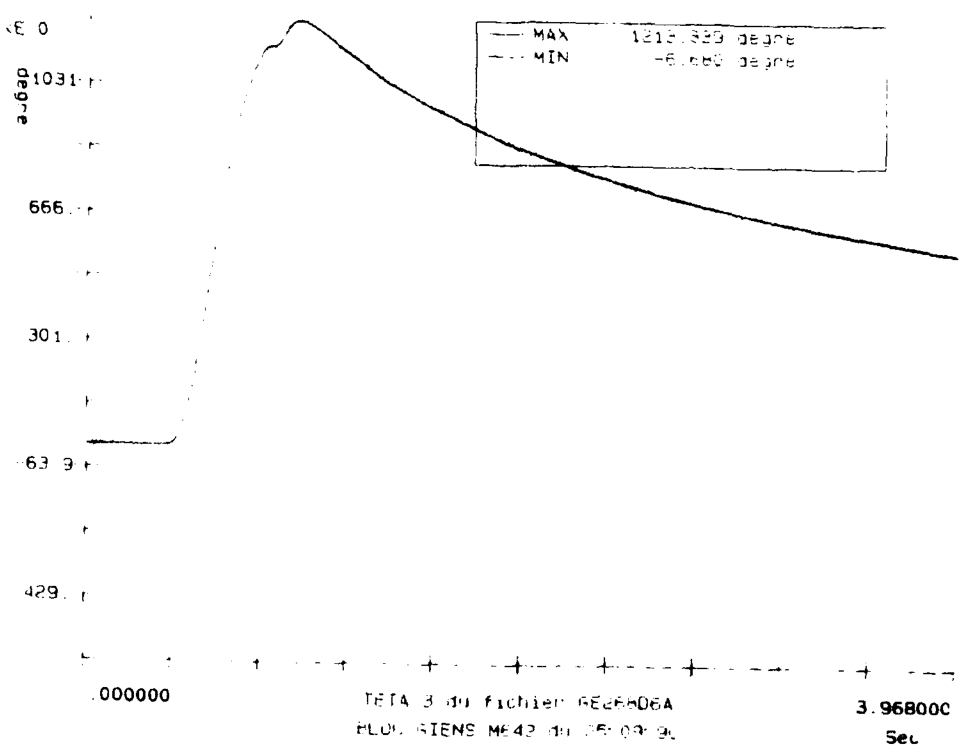
EVOLUTION DU FLUX DE RAYONNEMENT

ANNEXE A-2

IMPACT DE JET DE PROPULSEUR



DISPOSITIF D'ESSAI



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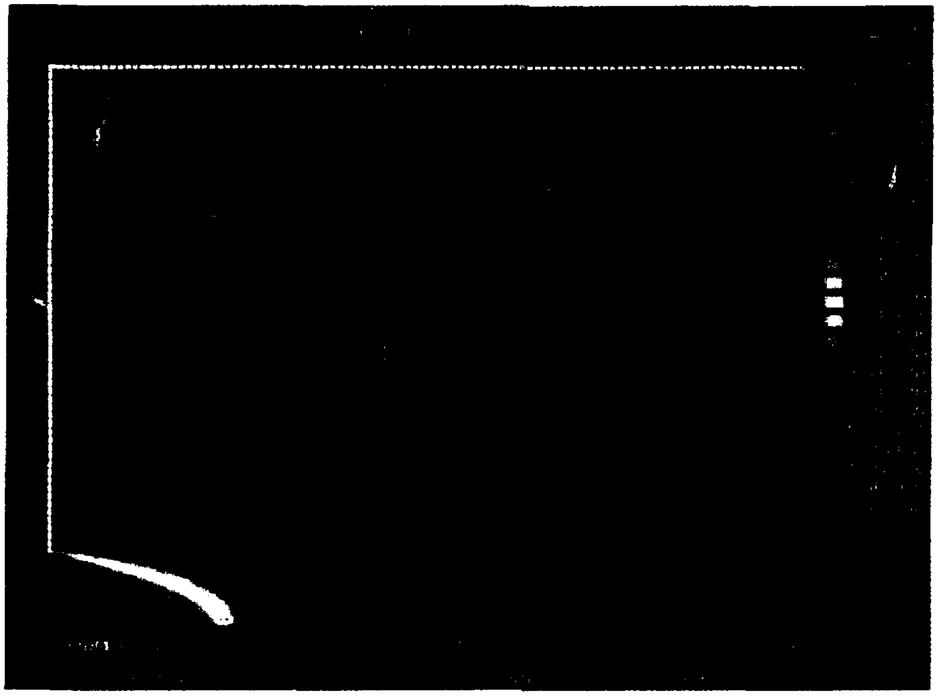
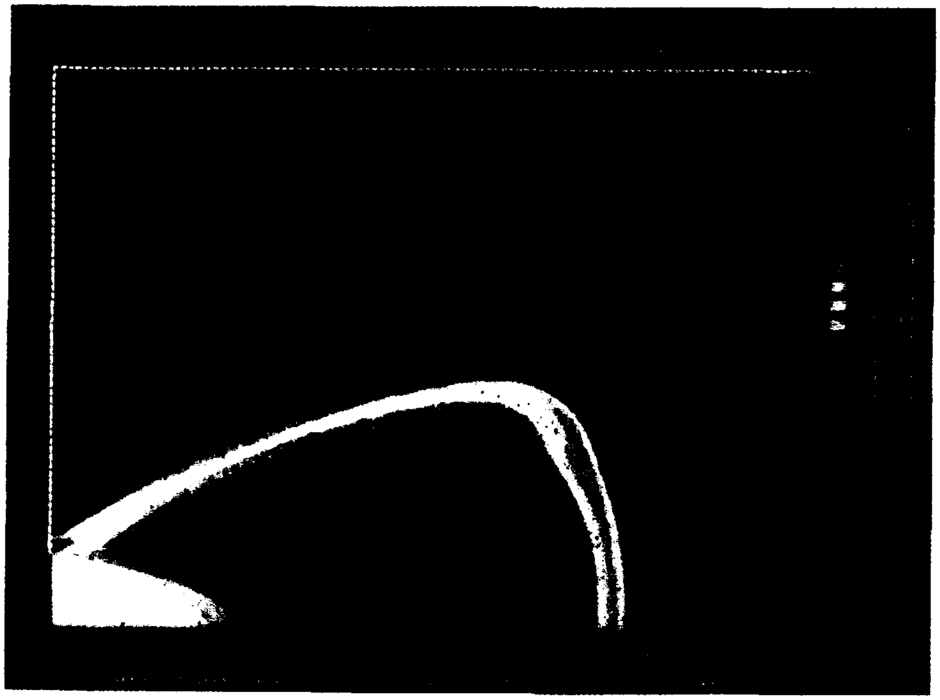
TEMPERATURE SUR LA PLAQUE

ANNEXE A-3

JET A LA SORTIE DE LA TUYERE



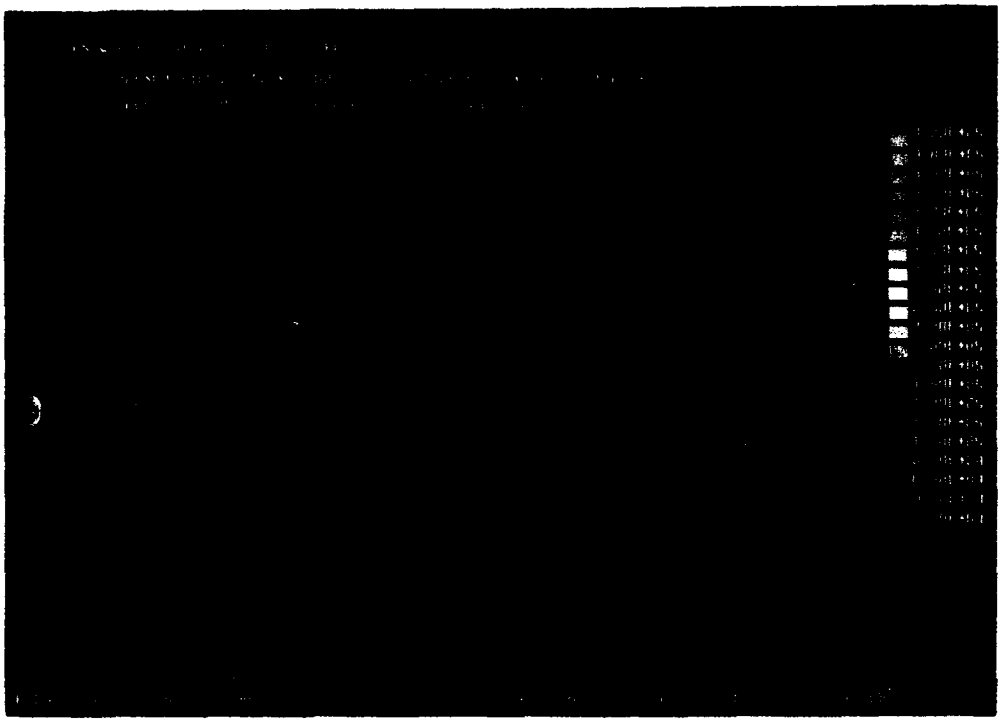
PRESSION A L'INSTANT t = 1 ms



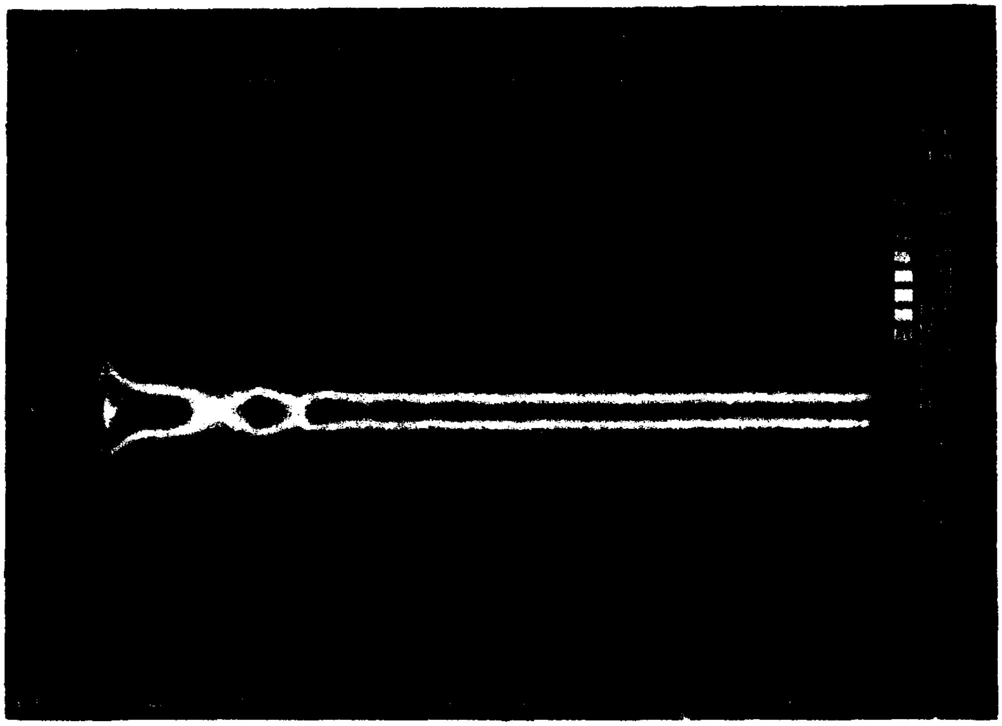
TEMPERATURE A L'INSTANT t = 1 ms

ANNEXE A-4.1

JET DANS L'ENSEMBLE SOUTE-PLENUM



PRESSION A L'INSTANT t = 250 ms

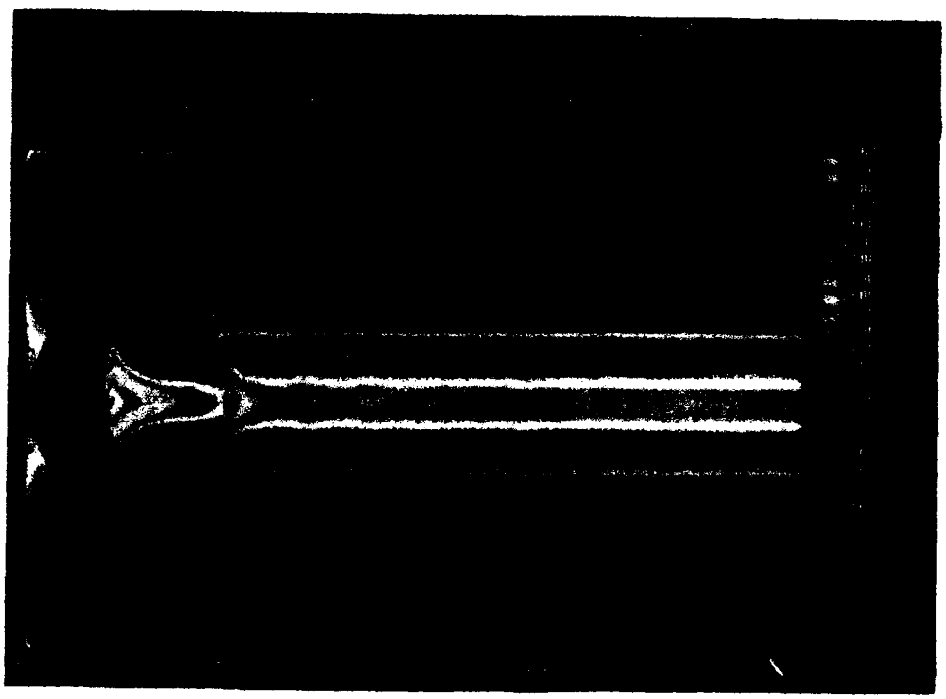


TEMPERATURE A L'INSTANT t = 250 ms

ANNEXE A-4.2

JET DANS L'ENSEMBLE SOUTE-PLENUM

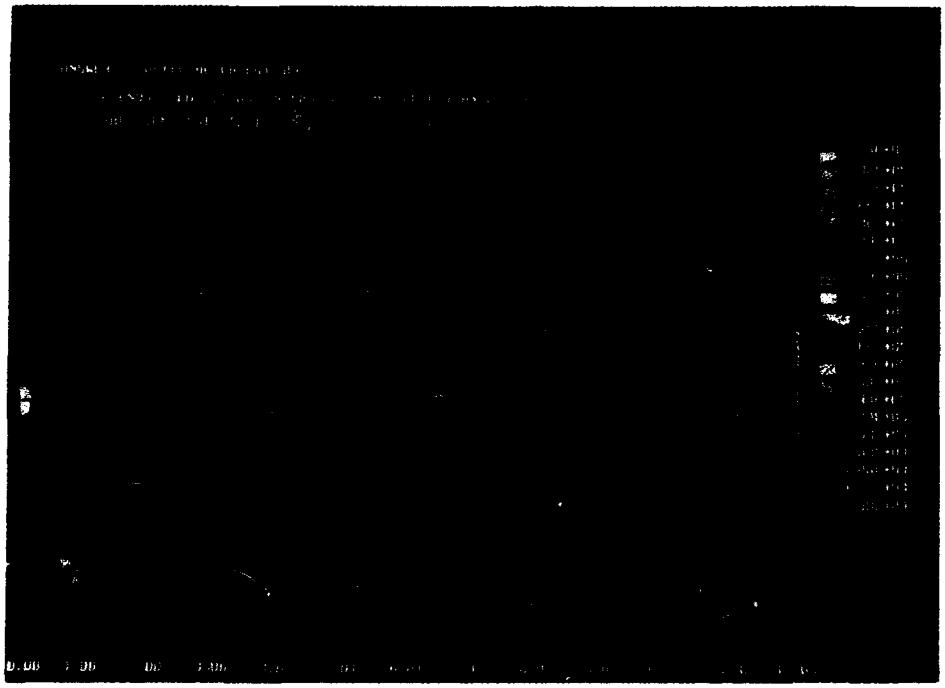
PRESSION A L'INSTANT t = 500 ms



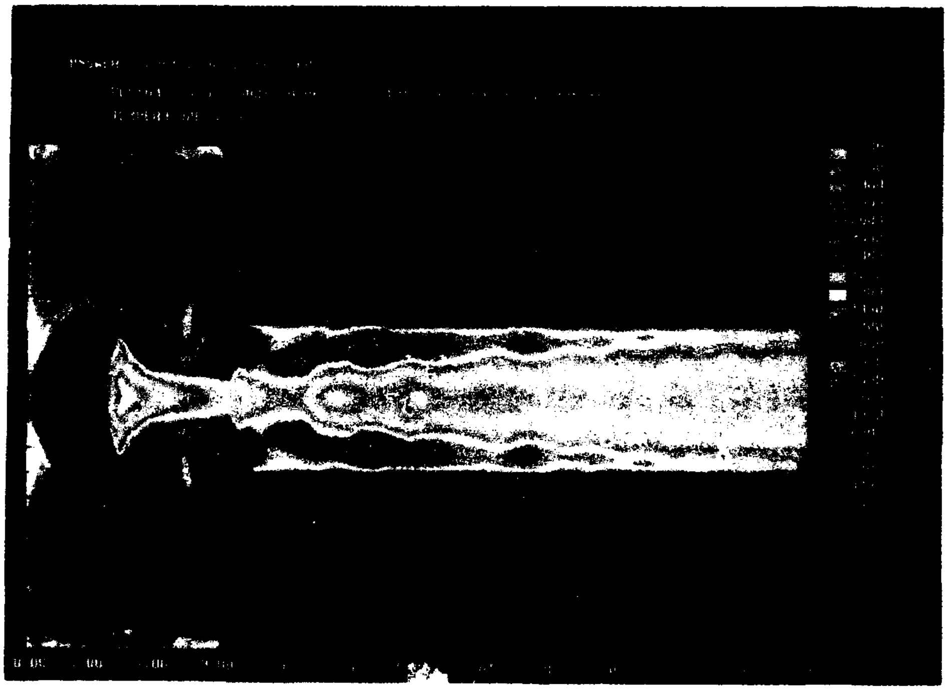
TEMPERATURE A L'INSTANT t = 500 ms

ANNEXE A-5

JET DANS L'ENSEMBLE SOUTE-PLENUM



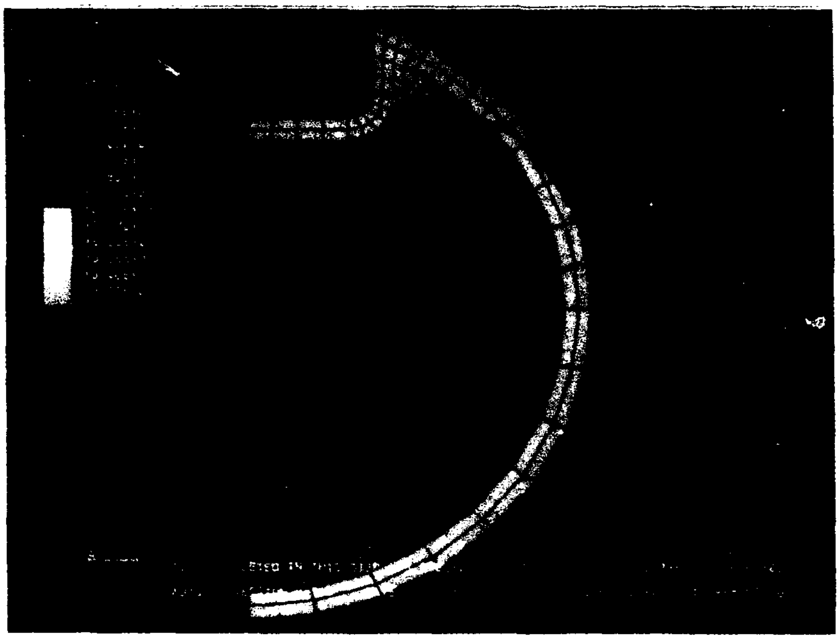
PRESSION A L'ETAT STATIONNAIRE

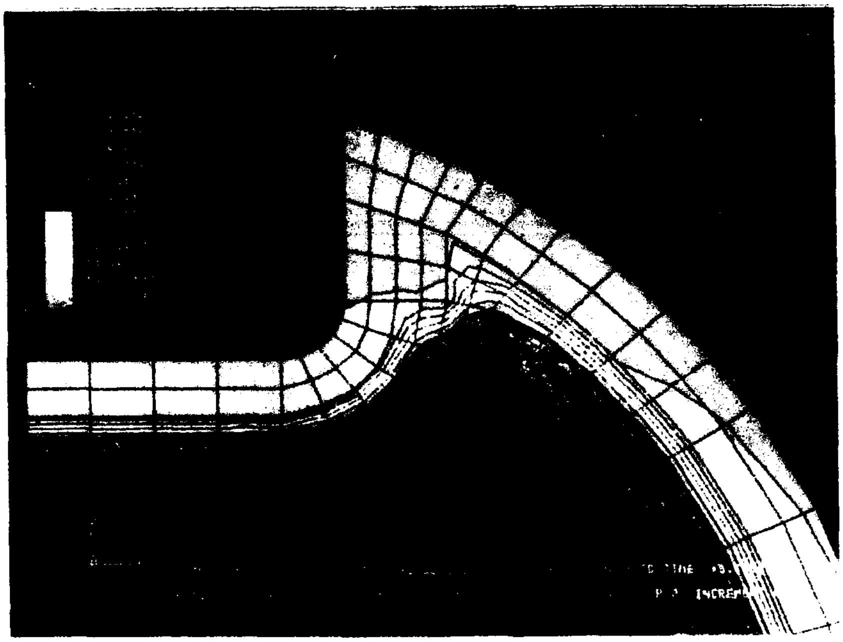


TEMPERATURE A L'ETAT STATIONNAIRE

ANNEXE A-6

MUNITION SOUMISE A UN INCENDIE

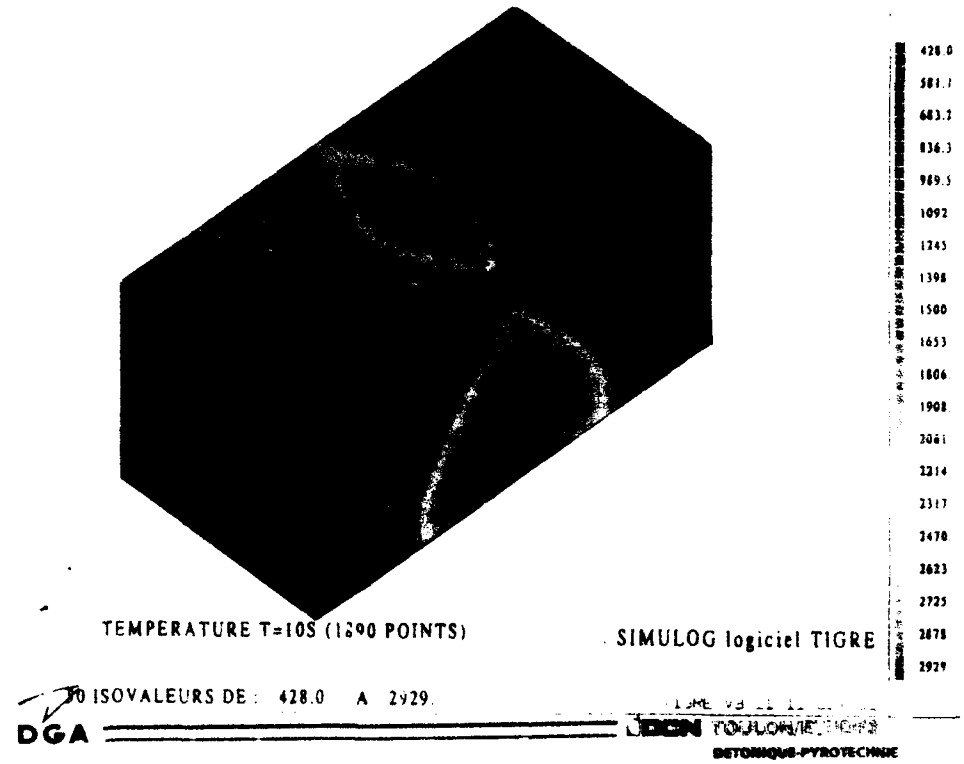




TEMPERATURE AU TEMPS DE REACTION

ANNEXE A-7

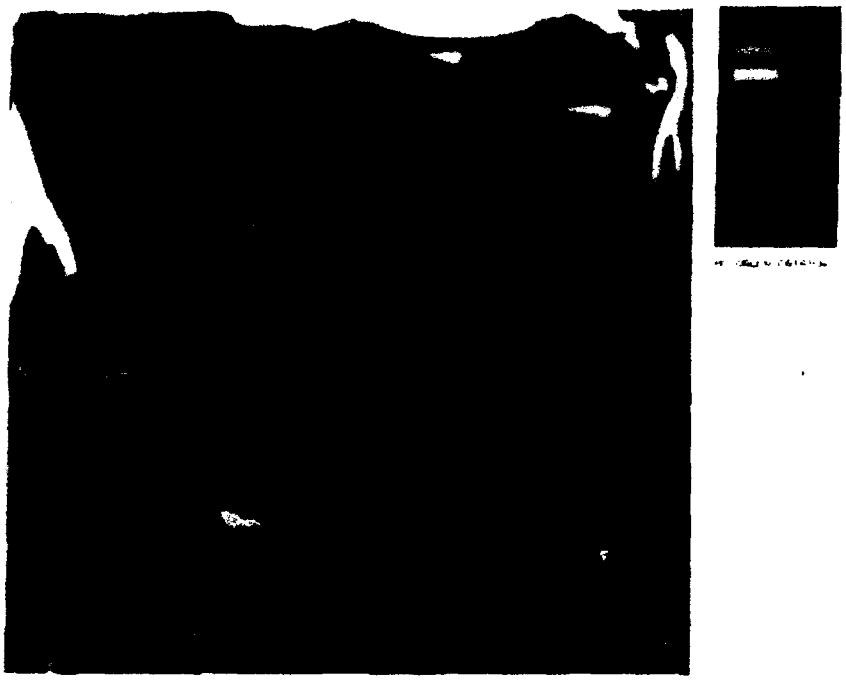
INCENDIE EN MILIEU CONFINE

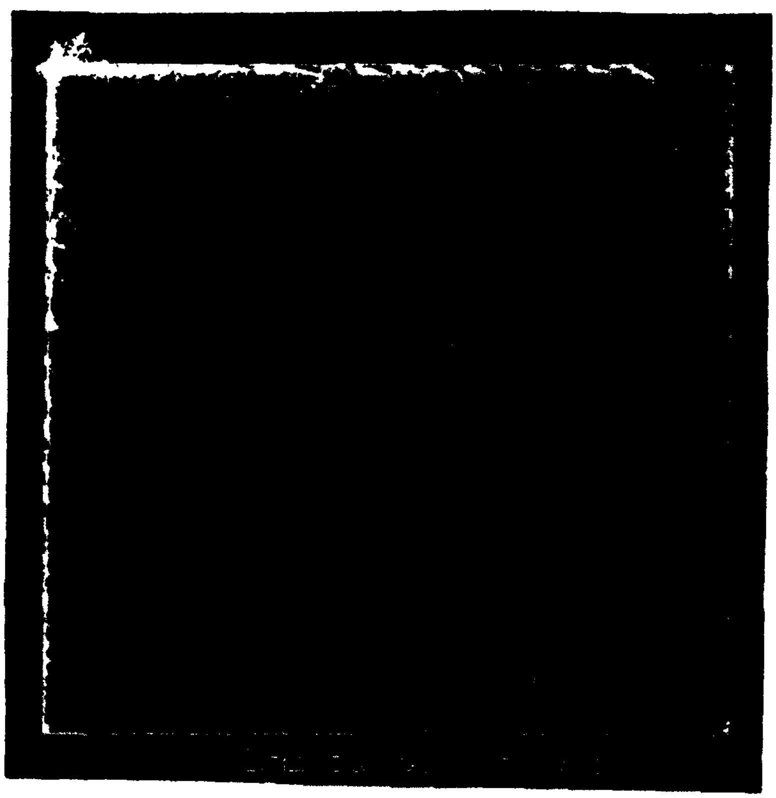


TEMPERATURE DE PEAU DU VOLUME EMETTEUR A L'INSTANT t = 10 s

ANNEXE A-8

INCENDIE EN MILIEU CONFINE





TEMPERATURE ET VITESSE DANS LE VOLUME RECEPTEUR A L'INSTANT t = 10 s

Numerical Modeling of the Shock Initiation of High Explosives

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1. SUMMARY

In the present work results are presented from two dimensional computations simulating impacts of various configurations of projectile against bare and covered high explosives. Under certain conditions the build-up of the detonation were obtained and sometimes the threshold conditions for the shock initiation were determined.

These calculations were performed using the nonlinear explicit finite-difference computer code PISCES 2D, in which the Forest-Fire burn rate model and the HOM equation of state were implemented by means of external user subroutines.

The following problems were analysed:

- APDS projectile impacting a warhead;
- shaped charge jet particles impacting an explosive reactive armour (ERA);
- flat-nosed projectiles impacting a bare explosive;
- flat-nosed projectiles impacting a covered explosive;
- round-nosed projectiles impacting a bare explosive.

In particular, in the case of the three last problems, the thresholds "detonation - non detonation", in plots of impact velocity versus projectile diameter, were numerically determined and directly compared with the experimental ones available in literature.

2. INTRODUCTION

Many situations exist were it is not certain whether and how a detonation builds up: warheads impacted by fragments or APDS (Armour Piercing Discarding Sabot) projectiles; reactive armours impacted by shaped charge jets or kinetic energy penetrators or EFPs (Explosively Formed Projectiles); problems of sympathetic detonations in the handling and storage of explosive materials; and generally all the phenomena where shock to detonation transitions in high explosives are possible.

It is therefore extremely important for the designer to avail of numerical tools capable of predicting the initiation of shocked high explosives. All over the world wide efforts have been performed in order to develop reliable numerical models which, in spite of the high computing costs, permit more flexibility of use than the semiempirical models.

The mechanism of shock initiation in high explosives is described as local decomposition at hot spots that are formed by shock interactions with density discontinuities. The liberated energy strengthens the shock so that as it interacts with additional inhomogeneities, hotter hot spots are formed and more of the explosive is decomposed. The shock wave grows stronger until a detonation begins. This mechanism of initiation can be numerically described by means of the Forest-Fire burn model, which gives the rate of explosive decomposition as a function of the local pressure.

When a projectile strikes a high explosive, the propagating shock wave may decay and die, failing to initiate a detonation, or it may be amplified and initiate a detonation in the explosive. In the present work some results are presented from two dimensional computations simulating the impact of projectiles against explosives and the following build-up or failure of a detonation. Such calculations were performed with the multi-purpose nonlinear explicit finite-difference computer code PISCES 2D, in which the Forest-Fire burn logic and the HOM equation of state were implemented by means of external user subroutines.

Various configurations of the explosive as well a wide range of diameters and impact velocities of the projectile were considered:

- APDS projectile impacting a warhead;
- shaped charge jet particles impacting an explosive reactive armour;
- flat-nosed projectiles impacting a bare explosive;
- flat-nosed projectiles impacting a covered explosive;
- round-nosed projectiles impacting a bare explosive.

3. MATERIAL MODELS.

3.1 Equation of State for Inert Materials.

The equation of state used to describe the inert materials was the Mie-Grueneisen equation. This equation was derived by assuming that Γ (gamma) is a function of the volume only and provides a means for extending the information of a known P-V relation (such as the Hugoniot) to other values of internal energy. For the Hugoniot reference equation we used a linear relationship between the shock velocity (U_s) and the particle velocity (U_p):

$$U_s = C_o + C_1 * U_p$$

where C_o is the bulk sound speed, and C_1 is the shock-particle velocity slope, which is assumed constant.

Detailed data for this equation of state may be found in Ref. 1. The coefficients used in our calculations are given in Table 1.

TABLE 1
Shock Parameters, Grueneisen Coefficients and Reference Densities for Inert Materials Used in the Calculations.

	C_0 (m/s)	C_1 -	Γ -	ρ_0 (kg/m3)
Copper	3920	1.488	1.96	8960
Steel	4580	1.490	1.67	7830
Tantalum	3414	1.201	1.40	16690
Tungsten	4040	1.230	1.54	19170

3.2 Constitutive Model for Inert Materials.
The Johnson-Cook constitutive model, which is suitable for metals subjected to large strains, high strain rates and high temperatures, was used in our calculations for copper, steel and tungsten. For the evaluation of the yield strength this model takes into account the strain hardening, the strain rate hardening and the thermal softening at increasing plastic strain, strain rate and temperature.

The relationship for the von Mises flow stress, Y, is:

$$Y = (A + B\ \varepsilon^{n})\ (1 + C\ \log\dot{\varepsilon}^{*})\ (1 - T^{*m})$$

where ε is the plastic strain, $\dot{\varepsilon}^{*} = \dot{\varepsilon}/\dot{\varepsilon}_o$ is the dimensionless plastic strain rate ($\dot{\varepsilon}_o$ = reference strain rate), and T^* is the homologous temperature

$$T^{*} = (T - T_{room})\ /\ (T_{melt} - T_{room})$$

A, B, n, C and m are material constants.

Detailed information and data for this constitutive model may be found in Ref. 2. In Table 2 the coefficients used in our calculations are reported.

TABLE 2
Johnson-Cook Constitutive Constants.

	A (MPa)	B (MPa)	n -	C -	m -
Copper	90	292	0.31	0.025	1.09
Steel	792	510	0.26	0.014	1.03
Tungsten	1506	177	0.12	0.016	1.00

For tantalum, the constitutive model proposed by Steinberg, Cochran and Guinan was adopted. Also this model is applicable at high rates of strain. In this model the relation valid for the von Mises yield strength is:

$$Y = Y_o\ [1 + \beta\ \varepsilon]^{n}\ [1 + C_1\ P/\mu^{1/3} + C_2\ (T\text{-}T_{room})]$$

subject to the limitation that:

$$Yo\ [1 + \beta\ \varepsilon]^{n} \leq Y_{max}$$

where P is pressure, μ is compression (defined as the initial specific volume divided by the specific volume) and Y_o, β, n, C_1 and C_2 are constants.

Detailed information and data for this constitutive model may be found in Ref. 3. In Table 3 the coefficients used in our calculations are reported.

TABLE 3
Steinberg - Cochran - Guinan Constitutive Constants.

	Yo (MPa)	Ymax (MPa)	β -	n -	C_1 (TPa-1)	C_2 (KK-1)
Tantalum	770	1100	10	0.1	14.5	-0.13

3.3 Equation of State for Explosives.
In our calculations the HOM equation of state was used. Such equation of state gives pressure as a function of specific volume, specific internal energy and mass fraction of the solid for solids, gases and mixtures.

Condensed Components

The equation of state for solids is expanded off the Hugoniot with the Grueneisen construction. The experimental Hugoniot data are expressed as linear fits of the shock and particle velocities. The Hugoniot temperatures are computed using the Walsh and Christian technique (Ref. 4) and fitted to a fourth-degree polynominal in logarithm of the volume.

Gas Components

The equation for gases is expanded off the BKW (Becker-Kistiakowsky-Wilson) detonation product isentrope fitted by a method of least squares to fourth-degree polynomials in logarithm of the variables.

Mixtures

The mixtures of condensed and gaseous products are solved assuming an ideal mixing (i.e. pressure and temperature equilibrium) of specific volumes of solids and gas, and energy partitioning according to mass fraction.

Detailed data for this equation of state may be found in Ref. 5. In Table 4 the coefficients used in our calculations are given.

3.4 Burn Rate Model.
The Forest Fire burn rate model was used in our calculations. This model permits the calculation of the burning resulting from the shock initiation of high explosives. It was developed for describing the decomposition rates as a function of the experimentally measured distance of "run to detonation" versus shock pressure (the Pop plot, named after its originator A. Popolato) and the reactive and non-reactive Hugoniot. in the Forest Fire model the burnt fraction, F, evolves in time according to the following pressure dependent equation:

$$dF/dt = (1 - F)\ \exp\ (X_1 + X_2 P + X_3 P^2 + \ldots + X_n P^{n-1})$$

Detailed information for this burning technique may be found in Ref. 5. In our calculation we used 14 terms in the polynomial expansion and in Table 5 the coefficients used in our calculations are reported.

TABLE 4
HOM Equation of State Input Parameters, Units (cm, gr, μs)

Explosive: Comp. B

HOM FOR CONDENSED COMPONENT

C	= 0.231
S	= 1.83
Fs	= -8.86751
Gs	= -79.73575
Hs	= -159.42898
Is	= -135.41104
Js	= -39.12747
GAMMAs	= 1.5
Cv (cal/g/K)	= 0.259
Vos	= 0.583090
C reactive	= 0.231
S reactive	= 2.50

HOM FOR GAS COMPONENT

A	= -3.525849
B	= -2.334292
C	= -0.597267
D	= 0.00304510
E	= -0.175226
K	= -1.560877
L	= 0.533121
M	= 0.0806311
N	= 0.00333817
O	= -0.000684400
Q	= 7.502781
R	= -0.441209
S	= 0.151293
T	= 0.0677883
U	= -0.0242403
Z	= 0.1
Cv' (cal/g/K)	= 0.5

Explosive: PBX9404

HOM FOR CONDENSED COMPONENT

C	= 0.2423
S	= 1.883
Fs	= -9.04187
Gs	= -71.31853
Hs	= -125.20498
Is	= -92.04242
Js	= -22.18938
GAMMAs	= 0.675
Cv (cal/g/K)	= 0.4
Vos	= 0.542299
C reactive	= 0.246
S reactive	= 2.53

HOM FOR GAS COMPONENT

A	= -3.5390626
B	= -2.5773759
C	= 0.2600754
D	= 0.01390836
E	= -0.01139630
K	= -1.6191304
L	= 0.5215185
M	= 0.06775066
N	= 0.004265243
O	= 0.0001046800
Q	= 7.3642292
R	= -0.4936582
S	= 0.02923531
T	= 0.03302774
U	= -0.01145325
Z	= 0.1
Cv' (cal/g/K)	= 0.5

TABLE 5

Forest Fire Input Parameters, Units (cm, gr, μs)

EXPLOSIVE: COMP. B		*EXPLOSIVE: PBX-9404*	
Pminimum	= 0.02	Pminimum	= 0.015
Pcj	= 0.284	Pcj	= 0.363
NTERMS	= 14	NTERMS	= 14
X1	= -1.035458E1	X1	= -8.3979133E0
X2	= +4.734274E2	X2	= +4.0524452E2
X3	= -1.675370E4	X3	= -1.2887960E4
X4	= +4.475675E5	X4	= +2.9889932E5
X5	= -8.493147E6	X5	= -4.7962437E6
X6	= +1.155593E8	X6	= +5.4017707E7
X7	= -1.140257E9	X7	= -4.3377143E8
X8	= +8.206591E9	X8	= +2.5068548E9
X9	= -4.298663E10	X9	= -1.0433259E10
X10	= +1.618379E11	X10	= +3.0950370E10
X11	= -4.260582E11	X11	= -6.3781135E10
X12	= +7.437677E11	X12	= +8.6704208E10
X13	= -7.728985E11	X13	= -6.9876089E10
X14	= +3.616778E11	X14	= +2.5277954E10

4. APDS PROJECTILE IMPACTING A WARHEAD.

In this section results are presented of a tungsten APDS projectile impacting a heavily confined high explosive simulating a warhead. The projectile is a tungsten 20-mm diameter 80-mm long penetrator which impacts at a velocity of 1700 m/s against PBX-9404 explosive with a 20-mm-thick steel cover. The initial geometry is shown in Fig. 1.

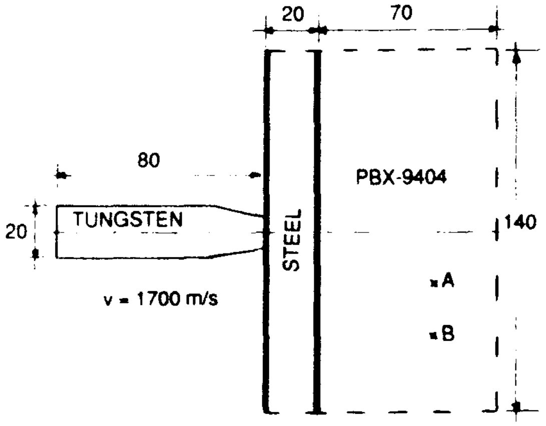

Figure 1 - Sketch of APDS Projectile Impacting a Warhead.

Due to the non-negligible material distortion which is expected for the target as well as for the projectile, the simulation was performed using only an Eulerian mesh. A uniform grid size of 2 mm was employed and proper boundary conditions (free flow directives) were also imposed in order to simulate a semi-infinite target in the direction of the axis of symmetry and an infinite target in the perpendicular direction.

In Fig. 2 three contour plots of density are reported which show three different steps of the penetration process. At t = 10 μs the projectile is still penetrating the confinement; at t = 30 μs the penetrator has completely perforated the steel cover and started the penetration of the high explosive; at t = 50 μs about 40 mm of the explosive has ben penetrated and the rest of the explosive is already detonated, at this time the simulation was stopped.

In two points inside the high explosive the pressure was recorded during the simulation. These points were located at distances of 20 mm and 40 mm from the axis of symmetry, and at a distance of 45 mm from the steel/explosive interface. The resulting pressure time histories, in which are evident the sharp peaks of the detonation front, are shown in Fig. 3.

In Fig. 4 a contour plot of pressure at t = 45 μs is reported. Also in this figure the initiation of the PBX-9404 and the presence of a detonation wave are evident.

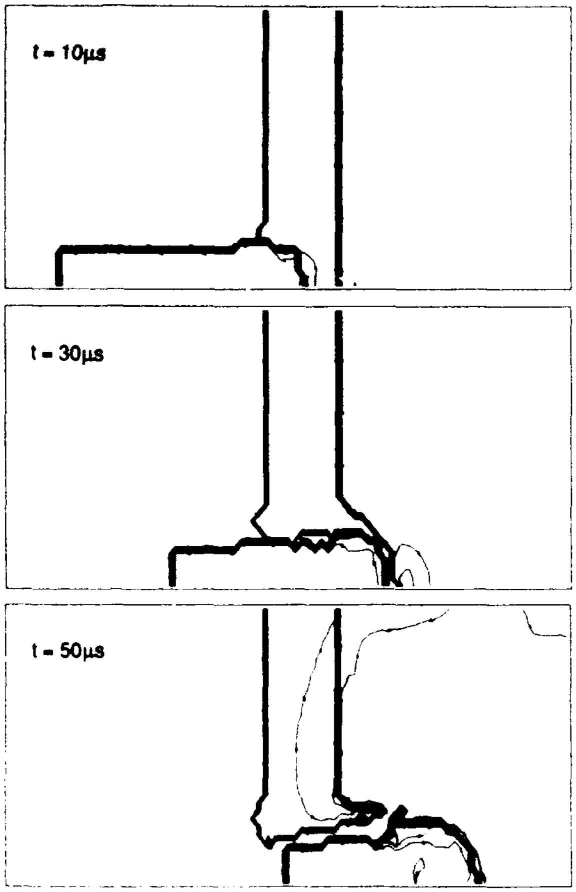

Figure 2 - APDS against Warhead, Contour Plots of Density at 10 μs, 30 μs and 50 μs.

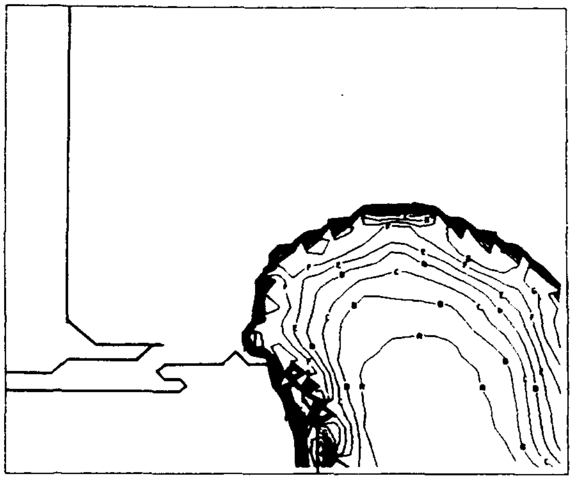

Figure 4 - APDS against Warhead, Contour Plot of Pressure at 45 μs.
Isobar Interval is 2 GPa, First Level is 10 GPa.

5. SHAPED CHARGE JET PARTICLE IMPACTING A REACTIVE ARMOUR.

In this section results are presented of shaped charge jet particles impacting an explosive reactive armour. In particular we have considered two possible jet particles which may be produced by the precursor charge of a tandem shaped charge warhead:

a. copper particle, diameter = 1.2 mm, length = 10 mm, velocity = 7000 m/s;

b. copper particle, diameter = 0.8 mm, length = 10 mm, velocity = 5000 m/s.

Both particles impact an ERA 5/5/5: 5 mm-thick Compound B explosive sandwiched between two 5 mm-thick steel plates. In Fig. 5 the initial geometry is reported

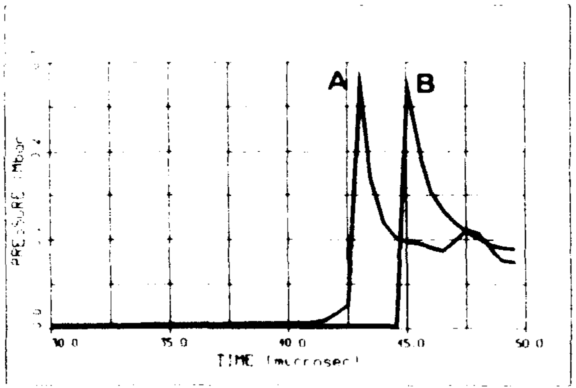

Figure 3 - APDS against Warhead, Time Histories of Pressure (0.1 Mbar = 10 GPa).
Position of Points A and B Is Indicated in Fig. 1.

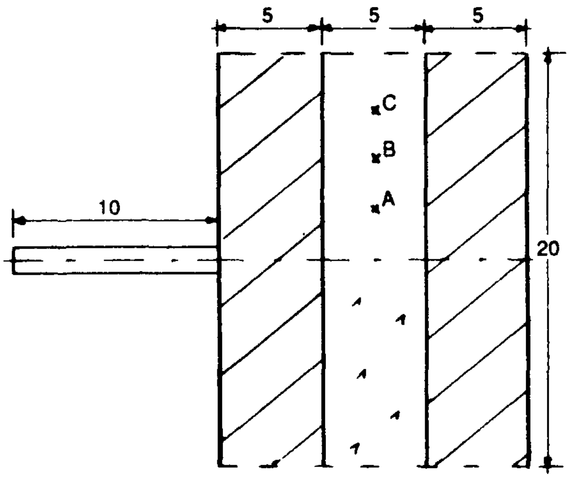

Figure 5 - Sketch of Copper Jet Particle (ϕ = 1.2 mm, v = 7000 m/s; ϕ = 0.8 mm, v = 5000 m/s) Impacting a ERA (Sandwich 5/5/5 Steel, Comp. B, Steel).

Also in this case the calculations were performed by means of a full Eulerian logics in order to prevent any problem arising from the distortion of the target material and the erosion of the penetrating jet particle. We used a uniform cell size of 0.2 mm leaving a certain amount of free space in front of ERA as well as in the rear side. At a distance of 10 mm perpendicular to the symmetry axis free flow boundary conditions (simulating infinite plates) were imposed.

a. *1.2 mm jet particle at 7000 m/s*
In Fig. 6 three different stages of the penetration process are shown by means of contour plots of density. The first plot corresponds at t = 0.5 µs; the jet particle is penetrating the first metal plate. The second plot corresponds at t = 2.5 µs; the jet particle has penetrated most of the explosive and a detonation wave is present in it. In the third plot, which corresponds at t = 4 µs, the penetration process is terminated and all the explosive is detonated.

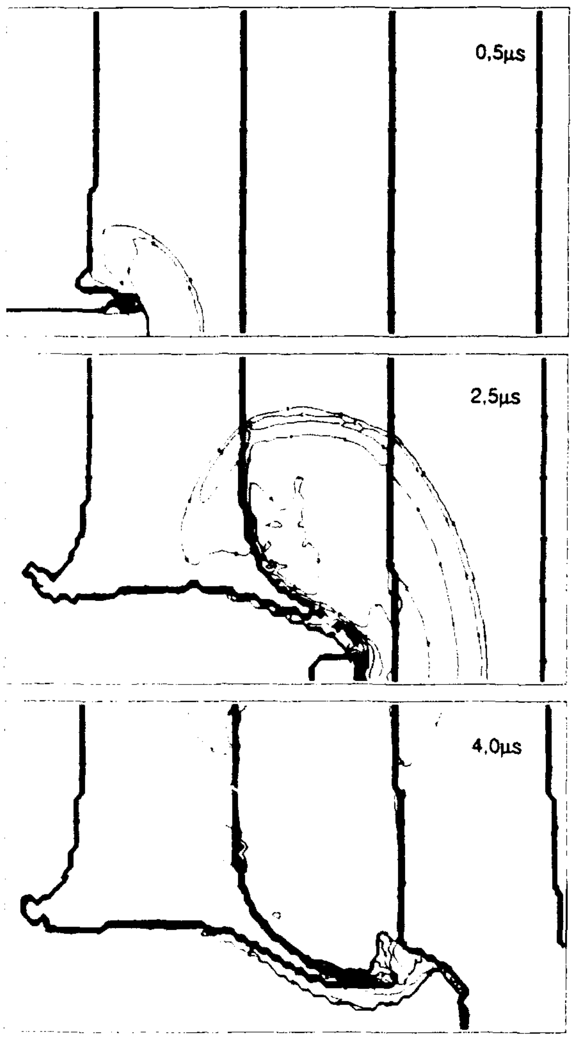

Figure 6 - Copper Jet Particle (ϕ = 1.2 mm, v = 7000 m/s) against ERA, Contour Plots of Density at 0.5 µs 2.5 µs and 4.0 µs.

Two contour plots of pressure at t = 2.0 µs and t = 2.5 µs are reported in Fig. 7. At t = 2 µs a detonation phenomena is clearly starting inside the explosive, the maximum pressure is not uniform in the detonation front, varying from about 20 GPa in the rear part (left) to 30 GPa in the front part (right). At t = 2.5 µs, instead, the detonation wave has already reached a stationary state with a uniform peak pressure.

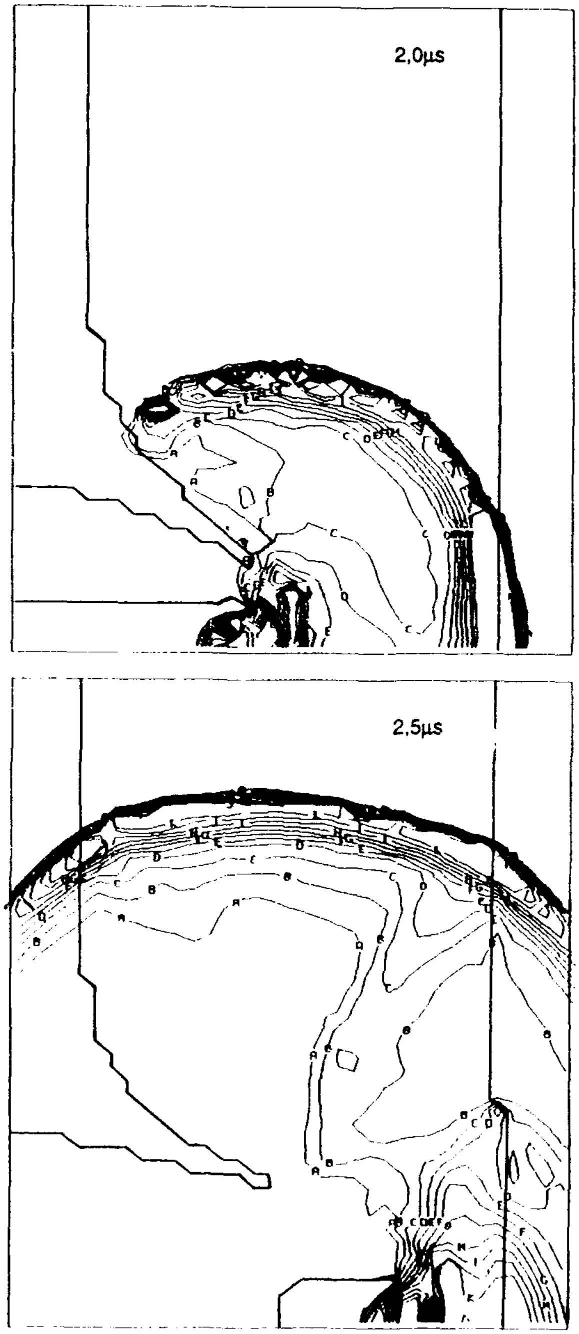

Figure 7 - Copper Jet Particle (ϕ = 1.2 mm, v = 7000 m/s) against ERA, Contour Plots of Pressure at 2.0 µs and 2.5 µs. Isobar Interval 2 GPa, First Level 10 GPa.

Time histories of pressure were also recorded in three different points inside the explosive. The three points were located in the middle of the explosive at the following distances from the axis of symmetry: 24 mm, 48 mm and 72 mm. The three time histories are reported in Fig. 8. In all the three plots a sharp peak is clearly present, typical of adetonation process, but in the first two points it is also evident the presence of a precursor shock which disappears in the third point. In order to better understand this, in Fig. 9 three other contour plots of pressure are shown in which only "low" pressure contour levels are reported. In the first plot, t = 1.5 μs, it is evident a spread shock wave propagating in the explosive. In the second plot, t = 2.0 μs, a detonation is started, but in the left side of the explosive a pressure ranging between 1 and 3 GPa is always present before the sharp peak. In the third plot, t = 2.5 μs, only a "normal" detonation wave is present: the pressure levels in the shock front are very near to each other, showing a very high pressure gradient.

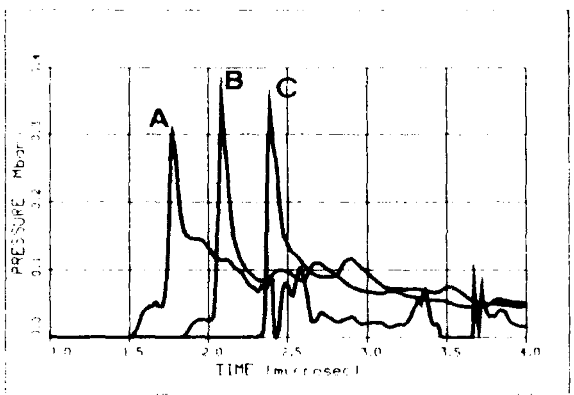

Figure 8 - Copper Jet Particle (ϕ = 1.2 mm, v = 7000 m/s) against ERA, Time Histories of Pressure (0.1 Mbar = 10 GPa).
Position of Points A, B and C Is Indicated in Fig. 5.

b. *0.8 mm jet particle at 5000 m/s*
In Fig. 10 three pressure time histories are shown. The three points were located in the middle of the explosive, in the same positions as the previously mentioned points (distances from the axis of symmetry: 24 mm, 48 mm and 72 mm). It is clear from this figure that in this case no detonation phenomena start as a consequence of the penetration by the jet particle.

A contour plot of density at t = 3.25 μs, approximately corresponding to t = 2.5 μs of the previous case, is shown in Fig. 11. In Fig. 12 a contour plot of pressure is reported at the same time. It is also evident in this figure that no detonation front is present in the explosive.

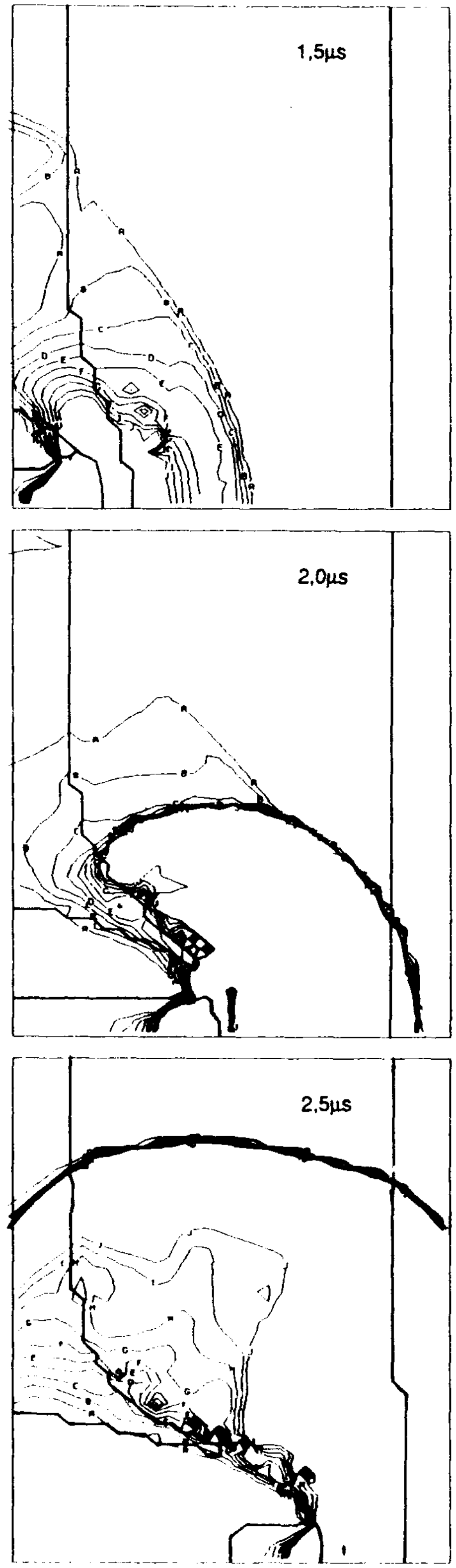

Figure 9 - Copper Jet Particle (ϕ = 1.2 mm, v = 7000 m/s) against ERA, Contour Plots of Pressure at 1.5 μs, 2.0 μs and 2.5 μs.
Isobar Interval 1 GPa, First Level 1 GPa.

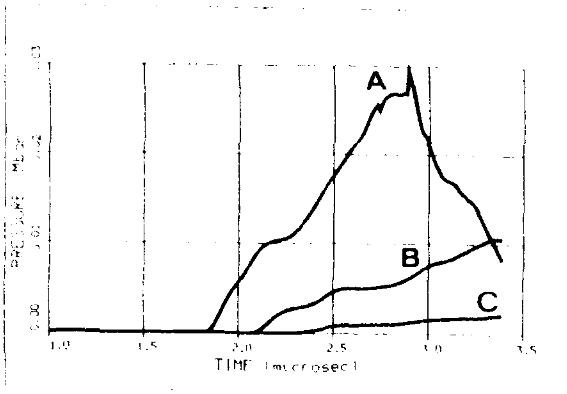

Figure 10 - Copper Jet Particle (ϕ = 0.8 mm, v = 5000 m/s) against ERA, Time Histories of Pressure (0.01 Mbar = 1 GPa).
Position of Points A, B and C Is Indicated in Fig. 5.

Figure 11 - Copper Jet Particle (ϕ = 0.8 mm, v = 5000 m/s) against ERA, Contour Plots of Density at 3.25 μs.

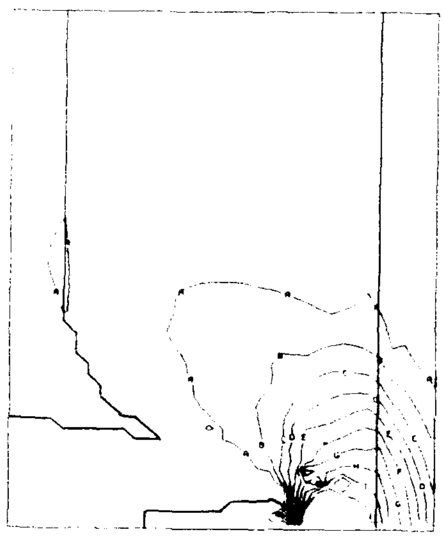

Figure 12 - Copper Jet Particle (ϕ = 0.8 mm, v = 5000 m/s) against ERA, Contour Plots of Pressure at 3.25 μs. Isobar Interval 1 GPa, First Level 1 GPa.

6. FLAT AND ROUND-NOSED PROJECTILES AGAINST BARE AND COVERED EXPLOSIVES.

In this section results are reported of computations of small flat-nosed and round-nosed steel projectiles impacting bare and covered PBX-9404 explosive. in this case the obtained results can be directly compared with the measured shock initiation thresholds reported in Ref. 6.

The three different configurations considered are:

a. flat-nosed steel projectile against bare PBX-9404; impact velocity range 250-1750 m/s, projectile diameter range 1.5-20 mm;
b. flat-nosed steel projectile against covered PBX-9404: 6 mm tantalum cover, impact velocity range 500-2000 m/s, projectile diameter range 5-20 mm;
c. round-nosed steel projectile against bare PBX-9404: impact velocity range 1000-2500 m/s, projectile diameter range 5-15 mm.

In all the three alternatives the projectile was simulated by means of the Lagrangian processor of the PISCES code, while for the target, explosive and cover, an Eulerian grid with a 0.5 mm uniform mesh size was used. The interaction between the Lagrangian grid and the Eulerian grid was possible by means of the standard polygon interactive logic of the PISCES code. This hybrid logics was usefully employed in consegue nce of the sufficiently small distortion suffered by the projectile Lagrangian mesh.

The calculations were performed using high explosive targets with diameters of 25 mm, in Fig. 13 the initial geometries of the three configurations are shown. In ref. 6 it is reported that diameters of 25.4 mm were used in the experiments. In the same work the authors state that such explosive diameters can be usefully employed for projectile diameters up to 20.3 mm without having the initiation processs disturbed by target side rarefactions. During the progress of this

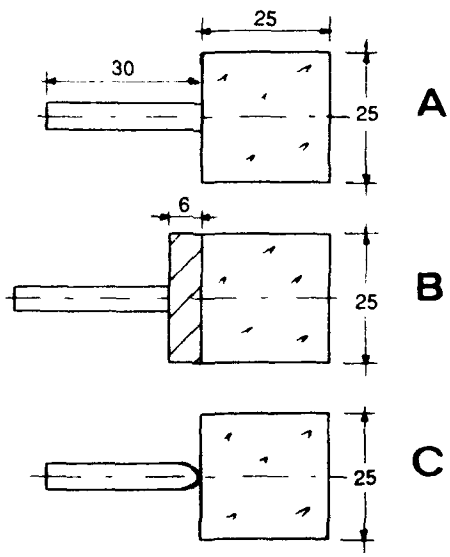

Figure 13 - Sketch of:
A) Flat-Nosed Steel Projectile Against Bare PBX-9404;
B) Flat-Nosed Steel Projectile against Covered PBX-9404 (6 mm-thick Tantalum);
C) Round-Nosed Steel Projectile against Bare PBX-9404.

work a check was done for a 18-mm diameter projectile impacting at 700 m/s the covered explosive configuration, simulating also a target with infinite lateral dimensions. In both cases, finite and infinite lateral dimensions, we had the initiation of a detonation and no important differences were detected in the pressure time histories of three points located on the symmetry axis of the explosive.

a. *Flat-Nosed Projectile/Bare Explosive.*
In Fig. 14 the computed as well as the measured detonation threshold curves are shown in a plot of impact velocity versus projectile diameter. In the same figure the limit points, calculated and measured, for detonation and non-detonation are also explicitely reported. Taking into account that the numerical data are the results of a completely a-priori theoretical prediction (no numerical test was performed to obtain better agreement changing the input material parameters or optimizing the numerical variables: grid size, impact logics, etc.) the agreement with the experimental data is quite satisfactory.

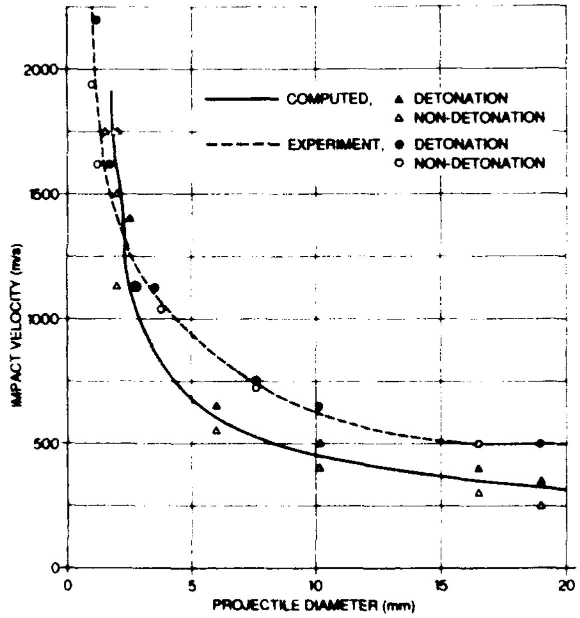

Figure 14 - Flat-Nosed Steel Projectile/Bare PBX-9404, Comparison between Numerically Predicted and Experimental Detonation Threshold Curve.

b. *Flat-Nosed Projectile/Covered Explosive.*
In Fig. 15 the computed and measured detonation threshold curves are shown in a plot of impact velocity versus projectile diameter. As before in the same figure the limit points for detonation and non-detonation are explicitely reported. Also in this case, considering that the numerical data are the results of a completely a-priori theoretical prediction, the agreement with the experimental data is quite good.

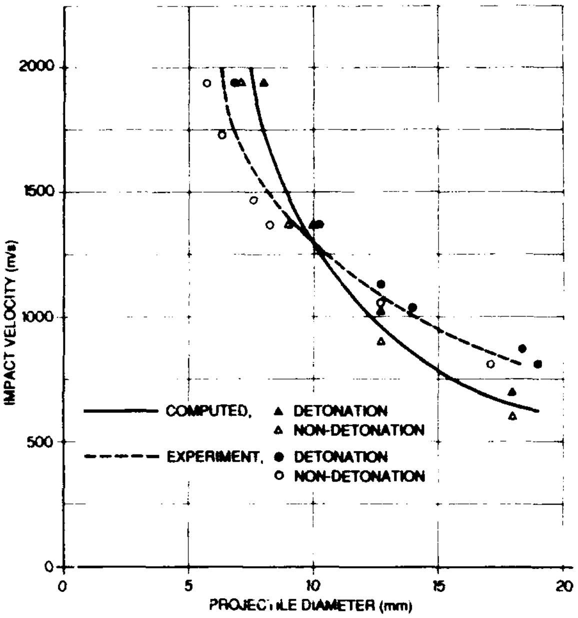

Figure 15 - Flat-Nosed Steel Projectile/6 mm-Ta-Covered PBX-9404, Comparison between Numerically Predicted and Experimental Detonation Threshold Curve.

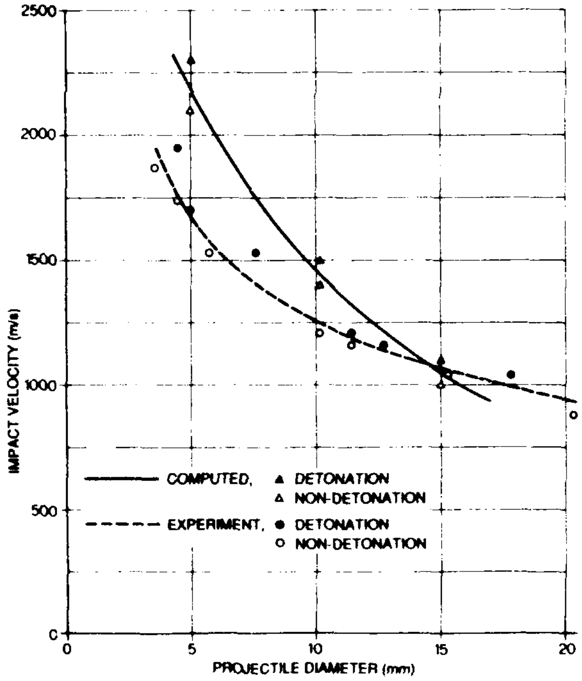

Figure 16 - Round-Nosed Steel Projectile/Bare PBX-9404, Comparison Between Numerically Predicted and Experimental Detonation Threshold Curve.

c. *Round-Nosed Projectile/Bare Explosive.*
In Fig. 16, as in the two previous ones, the computed and measured detonation threshold curves as well as the limit points for detonation and non-detonation are shown in a plot of impact velocity versus projectile diameter. Also in this last configuration the agreement with experiments is not bad.

All the numerical simulations show exactly the same trend of the experimental data, in particular it is confirmed that the shape of the nose of the projectile has a high influence on the detonation threshold of an explosive.

We can also notice that the level of agreement obtained during this work is not less than the one obtained at the Lawrence Livermore National Laboratory using an Eulerian code (called FLO) which employ the "nucleation and growth" rate model, Ref. 6.

7. CONCLUSIONS.

In the present work many results are presented from numerical simulations of impacts of various projectile configurations against covered and bare high explosives. It is shown that adding, actually by means of external user subroutines, to the two dimensional finite differences coupled Lagrangian-Eulerian PISCES code, the HOM equation of state with the Forest Fire burn rate model, it is possible to perform a very wide range of useful a-priori predictions in all possible circumstances where the problem exists to determine whether or not a detonation can start. Also if the agreement with reality may not be actually perfect, in each case the results obtained seems valuable and quite reliable.

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Discussion

COMMENT BY BOGGS, US: The author is complimented on a very nice presentation and very good work. Others should be encouraged to do similar work. Somehow we must be able to compare the results of the various analytical models run on common problems. I would hope that the NATO Insensitive Munitions Information Center could help facilitate such a round robin program of calculations on common problems.

ANSWER: Thank you.

PHENOMENE DE DETONATION PAR INFLUENCE : APPROCHE NUMERIQUE ET EXPERIMENTALE

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RESUME :

SNPE travaille depuis plusieurs années au développement d'explosifs peu sensibles. Un des objectifs est de démontrer la faisabilité de munitions fonctionnellement détonables et qui résistent à la détonation par influence. La réalisation de cet objectif requiert un effort multidisciplinaire:

- Développement d'explosifs très peu sensibles et de leurs systèmes d'amorçage.
- Analyse du phénomène de détonation par influence et mise au point de tests significatifs et des méthodes prédictives associées.
- Vérifications en vraie grandeur grâce à des modèles probatoires représentatifs de munitions de différents calibres, testés en situation "Donneur/receveur" ou en piles.

Le but de cet article est de décrire les méthodologies d'approches expérimentales et numériques.

ABSTRACT :

SNPE has been working for several years to develop insensitive high explosives. An SNPE objective is to demonstrate the feasability of munitions which are functionnaly detonable but which resist the sympathetic detonation. The achievement of this objective requires a multidisciplinary effort :

- Development of insensitive high explosives along with their boosters.
- Analysis of the sympathetic detonation phenomenon and development of meaningful tests and associated predictive methods.
- Full scale assessments based on probatory models which are representative of various munition sizes and types and are tested in donor/acceptor or stack tests.

The aim of this paper is to describe the experimental and numerical methodologies.

1 - INTRODUCTION

Selon l'approche de SNPE en matière de munitions à risques atténués et plus spécifiquement pour ce qui concerne les explosifs, trois niveaux croissants d'immunité [7] sont à prendre en compte :

- ***niveau 1*** : tenue à l'incendie
- ***niveau 2*** : niveau 1 plus une réactivité limitée aux impacts de balles et fragments légers
- ***niveau 3*** : niveau 2 et pas de détonation par influence.

Un des objectifs de SNPE dans le domaine des explosifs est d'atteindre le niveau 3, c'est à dire de démontrer la faisabilité de munitions fonctionnellement détonables mais qui ne détonent pas par influence, tout en conservant une réactivité limitée aux sollicitations plus classiques telles que le feu de kérozène, les impacts de balles ou fragments, voire les stimuli moins conventionnels comme l'échauffement très lent à 3,3°C/heure.

La réalisation de cet objectif ambitieux, et plus particulièrement la résolution du problème que pose la détonation par influence, requiert une approche

multidisciplinaire :

I développement d'explosifs peu sensibles et aux performances suffisantes,

II développement de relais d'amorçage adaptés à ces explosifs,

III analyse du phénomène de detonation par influence et mise au point de tests significatifs et de méthodes prédictives,

IV recherche de concepts d'architectures de munitions permettant l'emploi de matériaux explosifs classiques

V vérifications expérimentales en vraie grandeur grâce à des maquettes représentatives de divers types de munitions et testées en configurations "donneur/receveur" ou en piles significatives des conditions de stockage,

VI optimisation finale (explosifs, relais, architecture, procédés ...) associée à une munition spécifique en fonction des performances requises.

Tous ces thèmes sont entrepris simultanément par SNPE, avec toutefois une approche au cas par cas pour ce qui concerne le point VI. Le propos de cet article est de décrire cette approche globale grâce à quelques exemples qui relèvent des points I, III et V.

2 - DEVELOPPEMENT D'EXPLOSIFS PEU SENSIBLES

SNPE apporte sa contribution depuis plusieurs années au développement d'explosifs peu sensibles [1 à 8]. La plupart de nos explosifs composites à liants polymérisables atteignent déjà le niveau 2 d'immunité, mais SNPE porte un effort particulier sur les compositions à base d'Oxynitrotriazole (ONTA ou NTO pour les Anglo-saxons) afin d'atteindre le niveau 3, c'est à dire le niveau où la détonation par influence n'est plus à craindre [4, 5, 6, 8, 13, 14].

Pour illustrer nos progrès, nous avons sélectionné deux exemples de compositions à l'ONTA, représentatives du niveau 3 d'immunité, que nous comparerons à une composition performante plus classique à base d'octogène au niveau 2, et à une composition à usage sous-marin au comportement atypique. Ces explosifs sont décrits dans le tableau 1.

Quelques caractéristiques de performances sont données par le tableau 2 et des mesures de leurs sensibilités aux chocs par le tableau 3.

Plus de détails sur les compositions ORA86 et B 2214 sont disponibles par ailleurs [8, 15], en particulier sur leur capacité à résister aux impacts de balles, au feu de kérozène, aux impacts d'éclats lourds (M = 250 g), voire au jet de charge creuse.

B 2214 et B 3017 sont de bons candidats au classement en tant que "MDEPS", Matière Détonante Extrêmement Peu Sensible ("EIDS" : Extremely Insensitive Detonating Substance) de la classification 1.6 édictée par l'ONU [12].

3 - DETONATION PAR INFLUENCE, ANALYSE ET METHODES PREDICTIVES

Pour ce qui concerne les explosifs composites à liants polymérisables tels qu'élaborés par SNPE, il semble que la cause principale, responsable de la détonation par influence de piles de munitions, soit l'impact de la structure ou des fragments de la structure de la munition "donneuse" sur ses voisines.

Les autres aspects du problème (chocs aériens, effets thermiques divers) ne sont à considérer que dans des situations particulières où des focalisations de chocs aériens ou des concentrations de chaleur sont à redouter.

Le phénomène à prendre en compte semble donc être la transition choc/détonation des explosifs, sains ou endommagés. Les tests significatifs utilisés pour tester la sensibilité aux chocs de nos compositions sont les suivants :

- les tests d'IAD (ϕ40 ou 75mm,LSGT ou ELSGT)
- le test d'onde de choc calibrée [8]
- le test du coin [10]
- le test d'impact d'éclat lourd proposé par le GERBAM [8,15]

Les méthodes numériques prédictives relèvent également de la transition choc/détonation. Deux méthodes principales existent, qui nécessitent des caractérisations expérimentales préalables différentes :

- Dans une configuration donnée, les pressions des

chocs qui se propagent dans les munitions sollicitées sont évaluées numériquement à l'aide de logiciels adaptés (DYNA2D/3D [11] par exemple). Leurs amplitudes sont alors directement comparées aux pressions seuils issues de l'étalonnage des tests d'IAD, qui ont été calibrés numériquement et expérimentalement à l'aide de jauges pièzo-résistives. La figure 1 donne ces courbes d'étalonnage. Cette méthode n'assure pas toujours un diagnostic très fiable, surtout lorsque les dimensions des munitions sont grandes par rapport aux tests d'IAD.

- La 2ème méthode requiert une caractérisation expérimentale préalable plus complète des explosifs considérés en vue d'établir les modèles réactifs directement utilisables par les codes précités. Le diagnostic est alors accessible directement. Les figures 2 et 3 montrent l'usage que l'on peut faire de tels logiciels dans le cas de l'impact de fragment lourd ou dans une configuration "donneur/receveur" [15].

4 - CONFIGURATIONS EXPERIMENTALES

SNPE a identifié plusieurs concepts d'architectures de munitions susceptibles de ne pas détoner par influence. Ces concepts dépendent de la mission, de la nature et de la taille des munitions visées. Le concept le plus simple est, bien entendu, d'utiliser des explosifs insensibles associés à un système d'amorçage qui ne dégrade pas l'insensibilité de l'ensemble.

Dans le but de tester ces concepts et nos matériaux énergétiques dans des tailles réalistes, nous avons défini des maquettes cylindriques, représentatives de munitions génériques (figures 4 et 5).

Les essais de détonation par influence sont réalisés en configuration "donneur/receveur", dans une première étape destinée à faire un premier tri, puis en piles de neuf maquettes qui contiennent les explosifs réputés insensibles associés à leurs systèmes fonctionnels d'amorçage (figure 6).

Les tests sont instrumentés avec des jauges de surpression aérienne, des caméras rapides (500 à 30 000 images par seconde) situées sous différents angles de vue incluant une tour de 50m de hauteur, et des sondes à ionisation ou à court-circuit destinées à quantifier in situ la synchronisation des détonations éventuelles.

Grâce à cette instrumentation, aux observations locales et à l'examen post-mortem des maquettes ou de leurs restes, il est possible d'effectuer un diagnostic fiable des tests.

5 - RESULTATS EXPERIMENTAUX

Les résultats obtenus concernant les configurations et compositions précédemment décrites sont les suivantes:

5.1. *Piles de neuf petites maquettes (ϕ 115 mm) :*

Dans ce cas, la masse totale d'explosifs est de l'ordre de 40 Kg.

ORA 86 :

Détonation totale de la pile en moins de 300 microsecondes, d'après le film réalisé à 30000 images par seconde et les sondes à ionisation.

B 2214 :

Pas de détonation par influence. Les huit maquettes entourant le donneur ont pu être retrouvées, plus ou moins endommagées dans un rayon de 350 m. Les maquettes initialement au contact du donneur (2, 5 et 6) étaient éventrées avec des signes de combustion partielle. Les autres ensembles (3, 4, 7, 8 et 9) étaient pratiquement réutilisables pour un autre essai.

B 3017 :

Pas de détonation par influence. Mêmes remarques que précédemment.

B 2211 :

Pas de détonation par influence. Mêmes remarques que précédemment.

L'utilisation de maquettes avec une structure métallique plus fine (6 ou 3 mm) ne modifie pas les résultats de non-détonation par influence pour les compositions B 2214 et B 3017, malgré l'accroissement notable des vitesses d'impact (tableau 4). Ce fait doit être vérifié pour la composition B 2211.

Les seuls différences significatives consistent en des distances de projections accrues (jusqu'à 550 m) et un dommage mécanique plus important des maquettes receveuses.

5.2. *Grosses maquettes (φ 273 mm) en configuration D/R:*

Dans ce cas, la masse totale d'explosif est de l'ordre de 75 kg, en fonction des densités des produits testés.

B 2211 :

Détonation par influence.

B 2214 :

Pas de détonation par influence. La maquette adjacente à la détonation est détruite mécaniquement. Des fragments partiellement brûlés d'explosif sont retrouvés dans un rayon de 100 m environ. L'association de maquettes inertes contenant deux concepts de relais d'amorçage nous a permis d'éliminer lors de ce test une mauvaise définition de relais.

5.3. *Piles de neuf grosses maquettes (φ 273 mm):*

Seule la composition B 2214 a été testée dans cette configuration. Dans ce cas, la pile était constituée de huit maquettes comportant au total 280 kg environ d'explosif, associées à une maquette contenant de l'inerte (n° 3 dans la pile).

Pour cet essai, deux versions de B 2214 spécialement colorées, en jaune et en rouge, ont été élaborées grâce au marquage du liant avec de petites quantités de colorants. Les maquettes 2, 5 et 6 étaient remplies de B 2214 jaune et les maquettes 4, 7, 8 et 9 de B 2214 rouge.

Une **non détonation par influence** a été constatée lors de ce test. Peu de B 2214 "jaune" a pu être retrouvé sur le terrain, alors que de grandes quantités de B 2214 rouge étaient dispersées dans un rayon de 300 m. Il est vraisemblable que les maquettes 2, 5 et 6 ont subi une déflagration. Seules les structures des maquettes 3, 9 et 7 ont pu être retrouvées, vides et éventrées, à des distances supérieures à 500 m.

6 - CONCLUSIONS:

Nous avons pu confirmer en vraie grandeur le caractère insensible des explosifs composites à l'ONTA. Ces produits, associés à des systèmes d'amorçage adaptés, sont d'excellents candidats au défi posé par l'exigence des munitions à risques atténués.

L'effort multidisciplinaire d'envergure engagé par SNPE, avec le soutien du STPE, dans les différents niveaux que représentent la synthèse de nouvelles molécules, la formulation d'explosifs composites, leurs caractérisations expérimentales et la modélisation de leurs comportements, porte ses fruits et doit permettre d'assurer le rendez-vous de la nouvelle génération de munitions MURAT.

REMERCIEMENTS

Travaux financés en partie par le Service Technique des Poudres et Explosifs du Ministère de la Défense.

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TABLEAU 1 : COMPOSITIONS (% MASSIQUES)

	HMX	*RDX*	*ONTA*	*P.A.*	*Alu.*	*LIANT*	*NIVEAU D'IMMUNITE*
ORA 86	86	/	/	/	/	14	2
B 2211	/	20	/	43	25	12	2/3
B 2214	12	/	72	/	/	16	3
B 3017	/	/	74	/	/	26	3

TABLEAU 2 : PERFORMANCES CARACTERISTIQUES

	DENSITE	***VITESSE DE (1) DETONATION (m/s)***	***PRESSION DE (2) DETONATION (GPa)***	***VITESSE DE(3) GURNEY (m/s)***
ORA 86	1,71	8380	30,0	2750
B 2211	1,80	≃ 5600	≃ 14,0	/
B 2214	1,63	7440	22,5	2210
B 3017	1,75	7780	26,6	2450

1) mesurées en ϕ 80 mm confiné
2) calculées par $\rho_0 D^2/4$
3) déduites de relèvements cylindriques divergents en ϕ 80 mm confiné.

TABLEAU 3 : SENSIBILITES AUX CHOCS

	INDICES D'APTITUDE A LA DETONATION (IAD)			
	I.A.D. ϕ 40 mm (L.S.G.T.) (2)		***I.A.D. ϕ 75 mm (E.L.S.G.T.) (3)***	
	Nombre (1) de cartes	***Pression induite max. (GPa)***	***Epaisseur de PMMA (mm)***	***Pression induite max. (GPa)***
ORA 86	160	5,0	90	3,5
B 2211	80	10,0	50	8,0
B 2214	25	14,5	40	9,5
B 3017	65	11,0	40	10,0

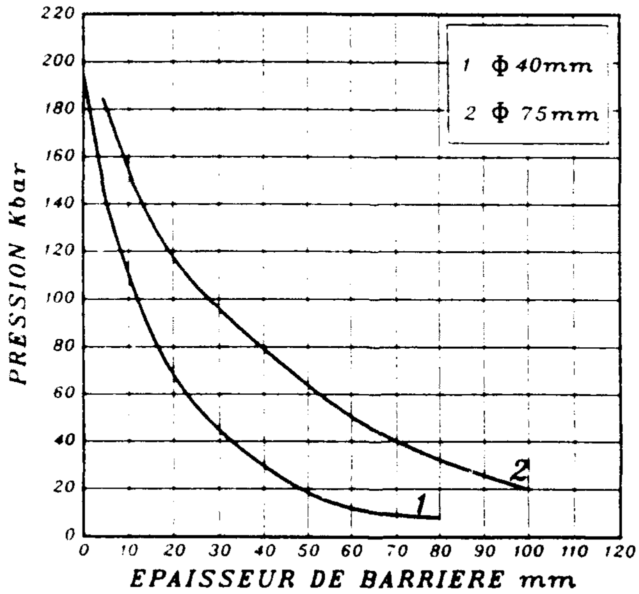
1) une carte Française équivaut à 70/95 carte US
2) Large Scale Gap Test
3) Expanded Large Scale Gap Test

TABLEAU 4

EPAISSEURS mm / COMPOSITIONS	VITESSES D'IMPACT (m/s) POUR UNE EXPANSION DE 25 mm — PETITES MAQUETTES 12,5	PETITES MAQUETTES 6	PETITES MAQUETTES 3	GROSSES MAQUETTES 12,5
B 2214	1000	1620 *	2050 *	1250
B 3017	1130	1720	2370	/
ORA 86	1160	/	/	/
B 2211	950	/	/	1200 *

* : Estimé

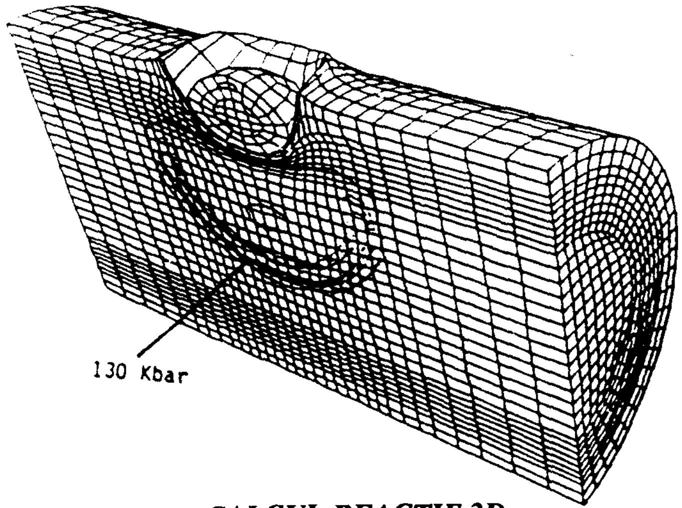
FIGURE 1



COURBES D'ETALONNAGE DES TESTS D'IAD (ϕ 40 = LSGT, ϕ 75 = ELSGT)

LES PRESSIONS SONT ESTIMEES DANS LA BARRIERE

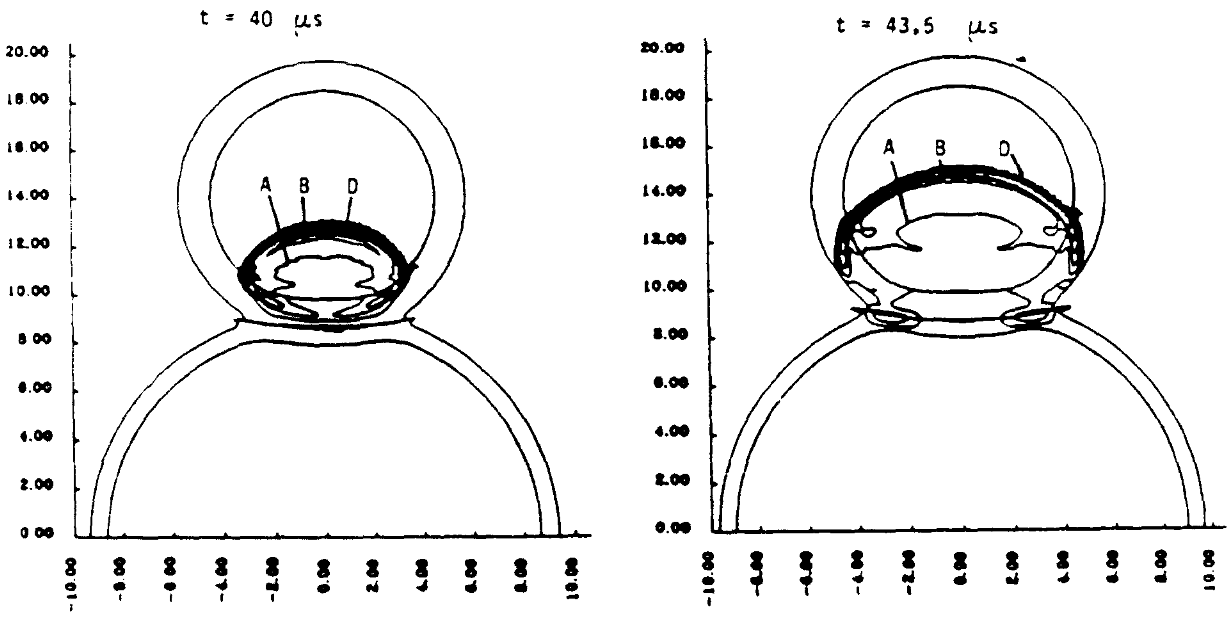
FIGURE 2



CALCUL REACTIF 3D
IMPACT DE BILLE LOURDE (ϕ 40) A V = 1800 m/s SUR ORA86

CONTOURS DE PRESSION

FIGURE 3

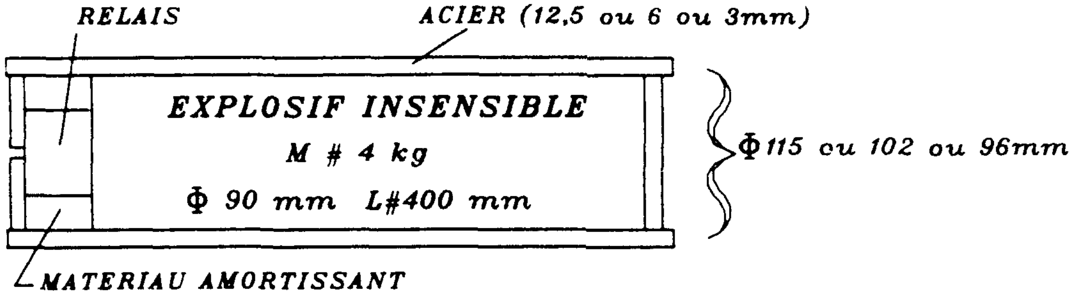


A = 100 kbar   B = 150 kbar   D = 250 kbar

CALCUL REACTIF 2D DE LA DETONATION PAR INFLUENCE
ORA 86 EN MAQUETTE ϕ 115 mm

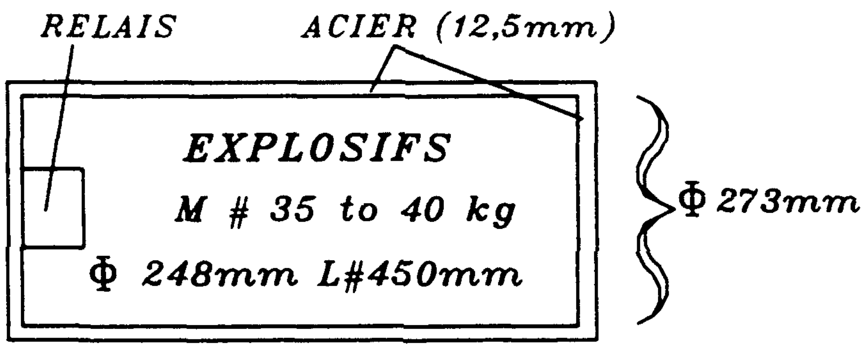
CONTOURS DE PRESSION

FIGURE 4



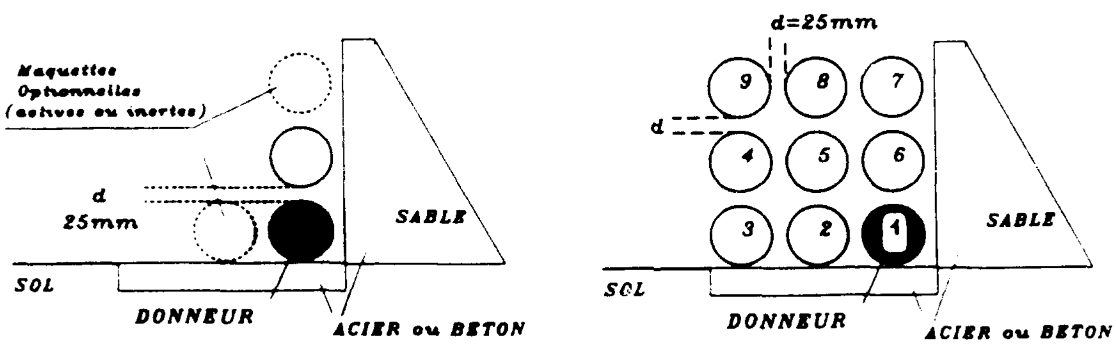
EXEMPLE DE PETITE MAQUETTE

FIGURE 5



EXEMPLE DE GROSSE MAQUETTE

FIGURE 6



CONFIGURATION DONNEUR/RECEVEUR ET PILE DE NEUF MAQUETTES ACTIVES (RELAIS EN PLACE)

Discussion

QUESTION BY VAN DER STEEN, THE NETHERLANDS: What binder did you use in compositions B2214 and B3017?

ANSWER: For B2214 it is a chemical HTPB binder and for B3017 it is a energetic binder where a polymer is plasticized by nitrate esters.

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14. Abstract

The Conference Proceedings contains the 23 papers and the Technical Evaluation Report presented at the Propulsion and Energetics Panel 78th A Specialists' Meeting on "Insensitive Munitions", which was held from 21st—23rd October 1991 in Bonn, Germany.
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Hazard reduction
Safety specification and policy
Munition survivability
Sensitivity reduction
Safety design
Impact resistance
Fire resistance

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